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ADVANCED FIREFLY ASSESSMENT GENERALIZED MECHANIZATION REQUIREMENTS REPORT

Northrop Aircraft Group
Hawthorne, California 90250

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Interim Report for Period 25 October 1978 to February 1979

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The requirements for the design of the Generalized Mechanization of the FIREFLY concept of Integrated Fire and Flight Control to be implemented in a digital simulation has been completed. This generalized mechanization consists of a set of equations, algorithms, and control laws capable of being programmed into an airborne digital computer which can be specialized to perform successfully in a variety of tactical aircraft with differing avionics sensors, fire control algorithms, control laws, flight control systems, and

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) weapon delivery modes.

The document first addresses the scope of the requirements analysis followed by a description of the analysis done in deriving the requirements of the generalized mechanization. Finally, the requirements are summarized in a section discussing them explicitly in relation to their place in the overall fire control system. A discussion of the work done on the FIREFLY II familiarization and initial analysis of two of the potential advanced concepts for evaluation is contained in the appendices.

FOREWORD

This interim report was prepared for the United States Air Force by the Aircraft Group of Northrop Corporation; 3901 W. Broadway, Hawthorne, CA 90250. It covers part of the work performed under Air Force Contract F33615-78-C-1503, Project 7629, Task 1007 (Advanced FIREFLY Assessment Program). The work reported in this interim report was performed from 25 October 1978 to February 1979.

The work described in this report was performed by Northrop under the direction of the Task I Leader Dr. S. J. Asseo. Dr. Asseo is a member of the Avionics Systems Analysis Department of Northrop, and reports to Mr. Herschel R. Melton, Program Manager of the Advanced FIREFLY Assessment Program. Other principal contributors to this report were R. J. Ardila, D. G. Myers, R. K. Shaffer, G. Whipple, R. Norton, Dr. Vance D. Norum, and M. A. Phillips.

The timely and notable contributions of the Air Force Project Engineer Mr. Ralph Bryan, (AFAL/RWT), are also gratefully acknowledged.

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ILLUSTRATIONS

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TABLES

LIST OF ACRONYMS

AAA	Anti-Aircraft Artillery
A/A	Air-to-Air
AAG	Air-to-Air Gunnery
AFAL	Air Force Avionics Laboratory
AFFA	Advanced FIREFLY Assessment
A/G	Air-to-Ground
AGG	Air-to-Ground Gunnery
ATF	Advanced Tactical Fighter
CAS	Control Augmentation System
CCRP	Continuously Computed Release Point
CCV	Control Configured Vehicle
CG	Center of Gravity
EO	Electro-optical
FCS	Flight Control System
FSAP	FIREFLY Simulation and Analysis Program
GE	General Electric
GM	Generalized Mechanization
GMDR	Generalized Mechanization Design Report
GMRR	Generalized Mechanization Requirements Report
HARS	Heading Attitude Reference System
IFFC	Integrated Fire Flight Control
INS	Inertial Navigation System
IMU	Inertial Measuring Unit
LOS	Line of Sight
MF	Measurement Function
MUX	Multiple Bus
OFP	Operational Flight Program
SAM	Surface-to-Air Missile
TAWDS	Terminal Aerial Weapon Delivery Simulation
TOF	Time Of Flight
VG	Vertical Gyro
VHSI	Very High Speed Integration
VLSI	Very Large Scale Integration

LIST OF SYMBOLS

SYMBOL	DEFINITION
A	Aim Point
a	Ownship acceleration, and Attacker acceleration
a_B	Aircraft body acceleration
a_b	Output of body mounted accelerometers
A_C	Ownship acceleration relative to earth
A_{C1}	INS acceleration
A_{C2}	Strapdown acceleration
A_E	Component of INS acceleration
A_G	Gravitational acceleration
A_I	Distance from Aim Point to Impact
A_N	Component of INS acceleration
a_R	Relative target acceleration
A_S	Sensed acceleration
a_t	Target acceleration
$a_{t_{scd}}$	Target acceleration in scd coordinate system
A_T	Perpendicular bisector of stick length, and Target acceleration
A_{T_ℓ}	Target acceleration component in ℓ direction
A_{T_m}	Target acceleration component in m direction
A_{T_s}	Target acceleration component in s direction
A_{T_x}	Target acceleration component in x direction
A_{T_y}	Target acceleration component in y direction
A_{T_z}	Target acceleration component in z direction
A_u	Strapdown IMU acceleration component in u direction
A_v	Strapdown IMU acceleration component in v direction
A_w	Strapdown IMU acceleration component in w direction
$[BP]$	Platform to body coordinate transformation
$[BH]$	HARS to body coordinate transformation

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
C	Attackers IMU or CG point, and
	Center of circular bombing trajectory
C_1	Sensor gain
C_2	Sensor gain
C_B	Ballistic coefficient
C_F	Distance to predicted impact point
CP	Distance from present attacker poisiton to a point directly above the target
C_P	Control law vector
C_{P_1}	Component of control law vector
C_{P_2}	Component of control law vector
C_{P_3}	Component of control law vector
CR	Distance from present attacker position to release point
d	Length of stick
D_1	Defined by equation A-6
D_f	Future range to target
D_{of}	Target position offset for bombing
DGO	Distance to go before turning for stick bombing
DB1	Distance loss due to gravity
$[E]$	Inertial to body coordinate transformation
e	Sight error angle, and
	Angular gun error
E_h	Helmet elevation angle
e_{Lv}	Component of gun pointing error
e_{Lw}	Component of gun pointint error
e_m	Off-boresight angle of traget LOS
E_s	Elevation angle of LOS with respect to body coordinates
e_v	Elevation error
e_w	Azimuth error

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
$[F]$	Attacker body to tracker coordinate transformtion
$\dot{F}$	Future target position
G	Gravity drop of weapon,
	Gravity vector,
	Attacker gun point, and
	Random excitation propagation matrix
G'	Ballistic vector along local vertical, and
	Vertical drop of weapon
g	Acceleration of gravity
GA	Projectile path length traveled along total velocity vector
GF	Future projectile path length
GI	Projectile path length to impact
GL	Gunline vector
GL_1	Component of gunline vector
GL_2	Component of gunline vector
GL_3	Component of gunline vector
$[H]$	Attacker body to helmet sight coordinate transformation
H	Observation matrix
h	Altitude
h_c	Altitude above target
H_{dg}	INS heading angle
I	Identity matrix, and
	Weapon impact point
I_{xz}	Moment of inertia about x axis
I_{zz}	Moment of inertia about z axis
J	Matrix for ownship acceleration model

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
K	Control loop gain
K_1	Control loop gain
K_2	Control loop gain
K_p	Control loop gain
K_{pp}	Control loop gain - pilot input
K_{pq}	Control loop gain - pilot input
K_R	Control loop gain
K_v	Control loop gain - gun pointing error
K_w	Control loop gain - gun pointing error
K_y	Control loop gain
KL	Kinematic lead vector
M	Variable gain
M_q	Stability derivative - pitch
M_{sp}	Measurement function specification parameter
N_p	Stability derivative - roll
N_r	Stability derivative - yaw
P	Roll rate, and
	Atmospheric pressure
P	Point directly above target
P_B	Parallex of bomb
P_C	Aircraft position vector
P_C	Command roll rate
P_G	Parallex, IMU to weapon
P_S	Parallex of sight
P_T	Target position vector
P_o	Sea level atmospheric pressure
P_1	End of stick bomb pattern
P_2	End of stick bomb pattern

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
q	Pitch rate
q_c	Commanded pitch rate
q_{cG}	Gun pitch rate commanded
q_{ec}	Commanded gun pitch rate
q_w	Pitch rate
r	yaw rate
R	Range to target
R_B	Ballistic vector
r_c	Commanded yaw rate
r_{CG}	Commanded gun yaw rate
R_D	Desired range for a hit
r_{ec}	Commanded gun yaw rate
R_G	Ground Range
R_M	Measured range to target
R_P	Range from IMU to a point above the impact point
R_R	Range to release point, and
	Ballistic vector along weapon velocity vector
R_{P2}	Components of R_P vector
R_{P3}	Components of R_P vector
R_{Rv}	Required range to target in attacker body axes
R_{Rw}	
R_s	Slant Range
$R_{s\ell m}$	Range in $s\ell m$ coordinate system
R_T	Turn radius for stick bombing
R_v	Actual range to target in attacker body axes
R_w	
R_1	Covariance of sensor measurement, and
	Stick bomb release point
R_2	Covariance of sensor measurement
	Stick bomb release point, and
	Radius of turning circle

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
R_X, R_Y, R_Z	Rectangular components of target radius vector
S	Attacker sight
SC	Steering command
SF	Future target position
SI	Predicted impact point
S_P	Unit vector along R_P
S_V	Unit vector along V_{CA}
$[T]$	Attacker body to [illegible]t coordinate transformation
T	Present target position, and Temperature
T_f	Time of flight
t_f	Time of flight
t_g	Time to go before bomb release
T_n	Helmet sight azimuth angle
t_i	Time
T_s	Azimuth angle of LOS in body coordinates
T_1	Defined by equation A-6
u	Process noise vector
U	Unit vector along u-body coordinate axis
v	Measurement noise
V	Aircraft velocity
V_a	Attackers air speed
V_B	Ownship velocity at bomb location
V_C	Ownship velocity
V_{CA}	Airspeed velocity
V_{CAX}	Initial horizontal velocity for China Lake algorithm

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
V_{CAY}	Initial vertical velocity for China Lake algorithm
V_D	Ground velocity, and
	Doppler velocity
V_E	Bomb ejection velocity, and
	Component of INS velocity
V_G	Attacker velocity relative to air mass at gun station
V_M	Muzzle velocity
V_N	Component of INS velocity
V_R	Target relative velocity
V_{RS}	Target relative velocity along antenna LOS
V_{RX}	Rectangular velocity coordinate
V_{RY}	Rectangular velocity coordinate
V_{RZ}	Rectangular velocity coordinate
V_T	Target inertial velocity
V_t	Target velocity
V_{TAS}	True air speed velocity
V_{TS}	Target velocity along LOS
$V_{ts\ell m}$	Target velocity in sℓm coordinate system
V_V	Component of INS velocity
W	Wind velocity
$[W]$	Wind to body coordinate transformation
X_1	Sensor measurement
X_2	Sensor measurement
Y	Observation vector
Z	Local vertical, and
	Root-sum-square of pitch, yaw, and roll rates

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
α	Angle of attack
α'	Direction Cosine of Air Velocity Vector
α'_m	Vane measured direction Cosine of Air Velocity Vector
β	Sideslip Angle, and Time Correlation Matrix
β'	Direction Cosine of Air Velocity Vector
β'_m	Vane Measured Direction Cosine of Air Velocity Vector
γ	Flight path angle, and Interface matrix
Γ	State Propigation Matrix
Δ	Update Time
ΔE	Elevation component of gun lead angle
ΔM	Predicted miss distance
ΔM_1	Component of predicted miss distance vector
ΔM_2	Component of predicted miss distance vector
ΔM_3	Component of predicted miss distance vector
ΔT	Azimuth component of gun lead angle
ΔU	Vector difference between U and a vector directed along the gun
ε	Error
ε_u	Error vector component
η	Process noise, and
	Angle from flight path to tangent to release circle for stick bombing
θ	Rotation matrix, and
	INS gimbal angle
Λ	Longitude
ρ	Atmospheric density
ρ	Sea level atmospheric density
Σ	Collection of statistical data
τ	Rack delay time
τ_g	Time to go before release command
$\emptyset$	INS gimbal angle,
	State transition propogation matrix, and
	Roll attitude angle
$\emptyset_{11}$	State transition matrix

LIST OF SYMBOLS — (continued)

SYMBOL	DEFINITION
ϕ_{12}	State transition matrix
ϕ_{13}	State transition matrix
ω	Angular rate
ω_a	Attacker angular rate
ω_c	Predicted angular rate, and LOS rate component
ω_{CG}	Commanded angular rate for gun
ω_d	LOS angular rate component
ω_s	Angular rate of gimbal axis
ω_t	Angular rate of target LOS, and Component of LOS rate
$\omega_{t\ell}$	Angular rate of LOS about ℓ axis
ω_{tm}	Angular rate of LOS about m axis
$\omega_{s\ell m}$	Angular rate of tracker coordinates
ω_1	Component of angular rate vector, ω
ω_2	Component of angular rate vector, ω
ω_3	Component of angular rate vector, ω

LIST OF SYMBOLS - (continued)

SYMBOL	DEFINITION
The coordinate systems used are right-handed and consist of the following:	
N, E, D	Inertial or earth-fixed coordinates; N - north, E - east, and D - down.
u, v, w	Attacker body coordintes; u - forward, v - out to right wing, and w - down.
u_w, v_w, w_w	Attacker wind coordinates; u - along attacker velocity relative to airmass, v_w - to the right, and w_w - down.
s, ℓ, m	Sight coordinates; s - along the target line-of-sight, ℓ - out to the right, and m - down.
t, c, d	Tracker coordinates, t - along the tracker axis, c - to the right, and d - down.
s_h, ℓ_h, m_h	Helmet sight coordinates, s_h - along the target sight, ℓ_h out to the right, and m_h - down.

Superscripts

^	Estimate
.	Derivative
_	Vector quanity
T	Vector transpose

1.0 INTRODUCTION

The Advanced FIREFLY Assessment (AFFA) Program extends and generalizes the Integrated Fire and Flight Control (IFFC) studies so effectively performed under the FIREFLY II Program. These studies have shown the potential for significant increases in aircraft survivability and effectiveness offered by integration of the fire control and flight control functions during the process of delivering a weapon to its target. To date, these studies have provided initial concepts and preliminary systems definitions. The AFFA Program will extend this work to operational applications, with specific avionics, and therefore requires a more versatile analysis tool for in-depth analysis.

The Advanced FIREFLY Assessment Program has as its primary goal the design of a Generalized Mechanization of FIREFLY concepts, the development of a digital simulation of the application of this Generalized Mechanization to a given aircraft (e.g., F-16) operating in a given mode (e.g., air-to-air gunnery), and the evaluation of the resulting designs. Generalization as used here implies the ability of each function in the mechanization to encompass different avionic subsystems operating in different aircraft in different modes. This Generalized Mechanization will also allow the effective investigation of Advanced FIREFLY applications beyond those cases considered in the FIREFLY II investigations.

Although the primary thrust of the AFFA Program involves determining a preferred fire control technology, associated avionics subsystem requirements and control law mechanizations, it is not possible to achieve the most effective integration with the flight control system without consideration of aircraft and flight control characteristics. Accordingly, the AFFA Program shall establish the extent to which consideration of detailed aircraft/flight control dynamics must be implemented, short of control system redesign. The goal here is clearly overall system performance as this is determined by dynamic interaction of the major functions and/or subsystems.

The AFFA Program is particularly timely because continuing rapid advances in microelectronics and the imminence of both Very Large Scale Integration (VLSI) and Very High Speed Integration (VHSI) make very large increases in computer capability both feasible and affordable. With such increased processing and memory capacity, much more sophisticated and complex algorithms can be mechanized to broaden the vistas of operational optimizations. As a result, the FIREFLY aircraft will be capable of more effective maneuvering prior to as well as during weapon release.

Currently each aircraft with its avionic sensors and associated flight control and fire control logic must be separately analyzed, simulated, and evaluated for its performance in a given tactical situation. When the mission scenario, aircraft, or sensor combination changes, extensive and costly effort results in arriving at a workable flight/fire control mechanization that is properly designed and evaluated. This difficulty motivates a generalized and modularized characterization of an integrated flight/fire control system mechanization and associated algorithms. The idea of such a Generalized Mechanization is to incorporate common functions (i.e., atmospheric and wind models, target models, attacker models, estimation algorithms, control logics, etc.) so as to not have to start from scratch each time the aircraft, sensor, and/or mission scenario change.

The term "Generalized Mechanization" will mean sets of equations, algorithms, and control laws capable of being programmed into an airborne digital computer which can be specialized to perform successfully in a variety of tactical aircraft with differing avionics sensors, fire control algorithms, control laws, flight control systems, and weapon delivery modes.

The design of the Generalized Fire Control Mechanization is of critical importance to the success of the AFFA Study. If the Generalized Mechanization is not sufficiently flexible, considerable duplication of effort may result during the development of the FIREFLY Simulation and Analysis Program and also during the design effort called for in Task 4. The Generalized Mechanization permits a unified approach to be taken in the overall avionics integration without getting unnecessarily bogged down in technical detail. Looking beyond the immediate aims of the FIREFLY Assessment Study, the generalized nature of the software architecture will be of great value in implementing the state estimator and fire control algorithms in an actual operational flight program. Therefore, a great deal of emphasis has been placed in developing a set of requirements for the fire control mechanization that has maximum generality with regard to sensor inputs and weapon delivery modes.

This report documents the requirements to which the AFFA Generalized Mechanization is to be designed. This is done by first addressing the scope of the Requirements Analysis followed by a description of the analysis done in deriving the requirements of the generalized mechanization in Section 3. Finally, the requirements are summarized in Section 4 discussing them explicitly in relation to their place in the overall fire control system.

A discussion of the work done on the FIREFLY II familiarization and initial analysis of two of the potential advanced concepts for evaluation is contained in the appendices.

2.0 GENERALIZED MECHANIZATION REQUIREMENTS ANALYSIS SCOPE

2.1 GOALS AND SCOPE OF THE GMRR

The goals and scope of the Generalized Mechanization Requirements Report (GMRR) are to specify detailed and explicit requirements for the Generalized Mechanization portion of a software tool called the FIREFLY Simulation and Analysis Program (FSAP). In this regard the GMRR is restricting the statement of GM requirements to:

1. An identification of a set of functions which comprise the Generalized Mechanization. This essentially characterizes the gross structure of the Generalized Mechanization and identifies specific interfaces.
2. An identification of all inputs and outputs of each function that is sufficient to encompass the major weaponry modes of air-air gunnery, air-ground gunnery, and bombing.
3. A specification of all interface requirements between functions and constraints on inputs/outputs of each function of the Generalized Mechanization.
4. An identification of all algorithms and their associated functional requirements for each Generalized Mechanization function.
5. An identification of coordinate frame options and state variables for each of the three weaponry modes.
6. An outline or preliminary statement of the mathematical equations which characterize the Generalized Mechanization.

A detailed specification of the error model requirements will be included as part of the Avionic Sensor functional requirements. A key issue which limits the scope of the GMRR is the boundary between the GMRR and the Generalized Mechanization Design Report (GMDR). In order to clarify this boundary, the scope of the content of the GMDR is presented below thereby showing how the combination of the GMRR and the GMDR feed into structuring the FIREFLY Simulation and Analysis Program.

GMDR SCOPE

1. Evaluation and choice of coordinate frames for different avionic subsystem combinations and different weaponry modes.
2. Evaluation and choice of state variables for different weaponry modes.

3. Evaluation and choice of algorithms within each function of the GM. This includes detailed statement of all equations to be implemented in the FIREFLY Simulation and Analysis program.

4. Identification of how the inputs are determined from the inputs for each function.

5. Justification of each assumption and identification of the limits on various parameters and variables to yield specific requirement within each GM function.

6. Identification of all assumptions made for each algorithm of each function.

The Generalized Mechanization (GM) consists of sets of equations, algorithms, and control laws capable of being programmed into an airborne digital computer which can be specialized to perform successfully in a variety of tactical aircraft with differing avionics sensors. Figure 1 illustrates how the GM relates to the aircraft and to the other elements of the tactical environment.

Requirements on the GM will be imposed by the following considerations:

1. the mathematical adequacy of the system dynamics formulation,
2. software requirements and,
3. hardware requirements.

Each of these will result in constraints and limitations on the GM. The current version of this document focuses on the mathematical adequacy of the GM and on the variety of sensors addressed by the GM. Requirements imposed upon the GM due to the other considerations will be determined.

Figure 2 illustrates the development flow for the Generalized Mechanization Requirements. Section 3.0 of this report will discuss the Generalized Mechanization Requirements Analysis and Section 4.0 will contain a complete presentation of the resulting requirements.

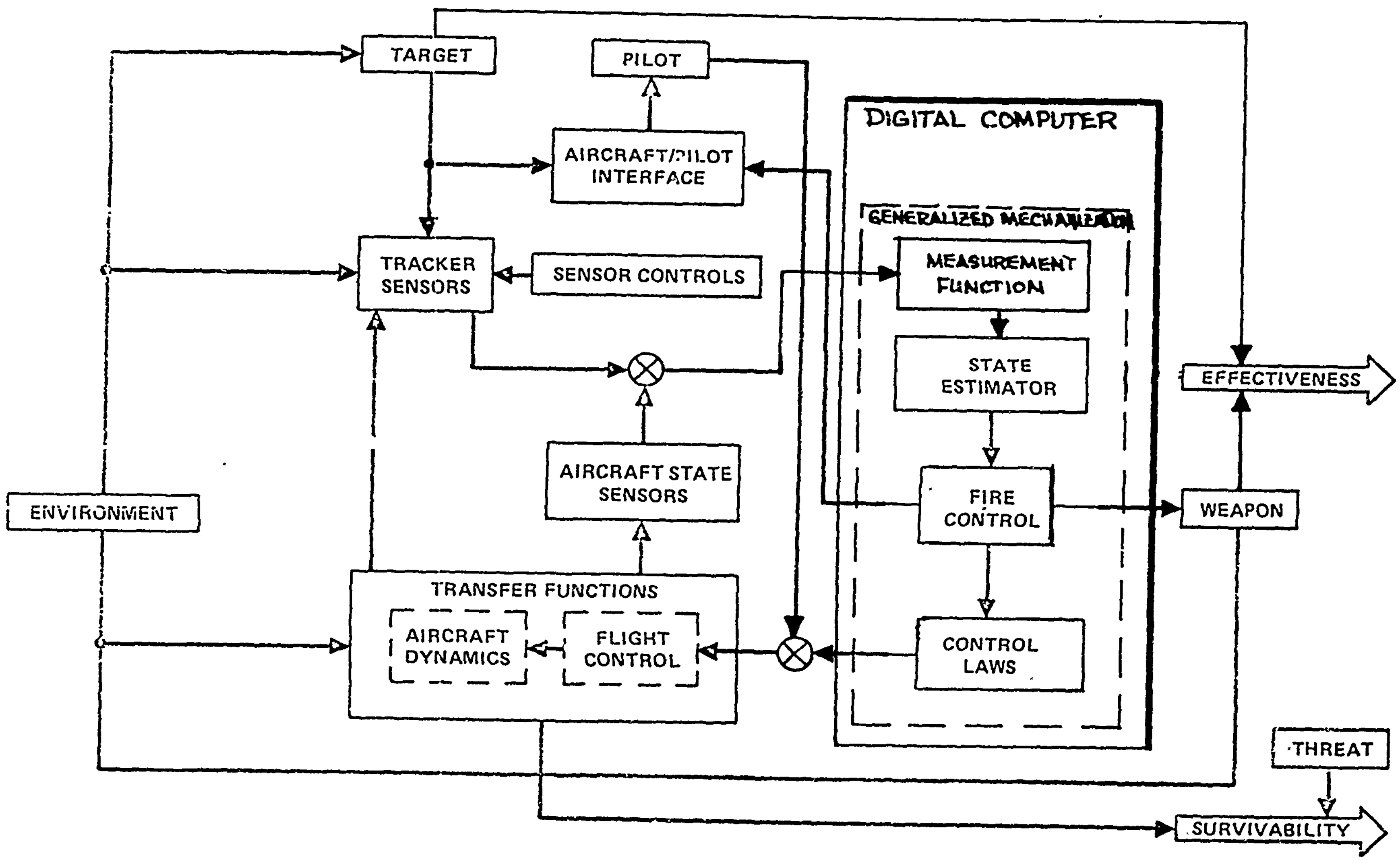


FIGURE 1. FUNCTIONAL FLOW

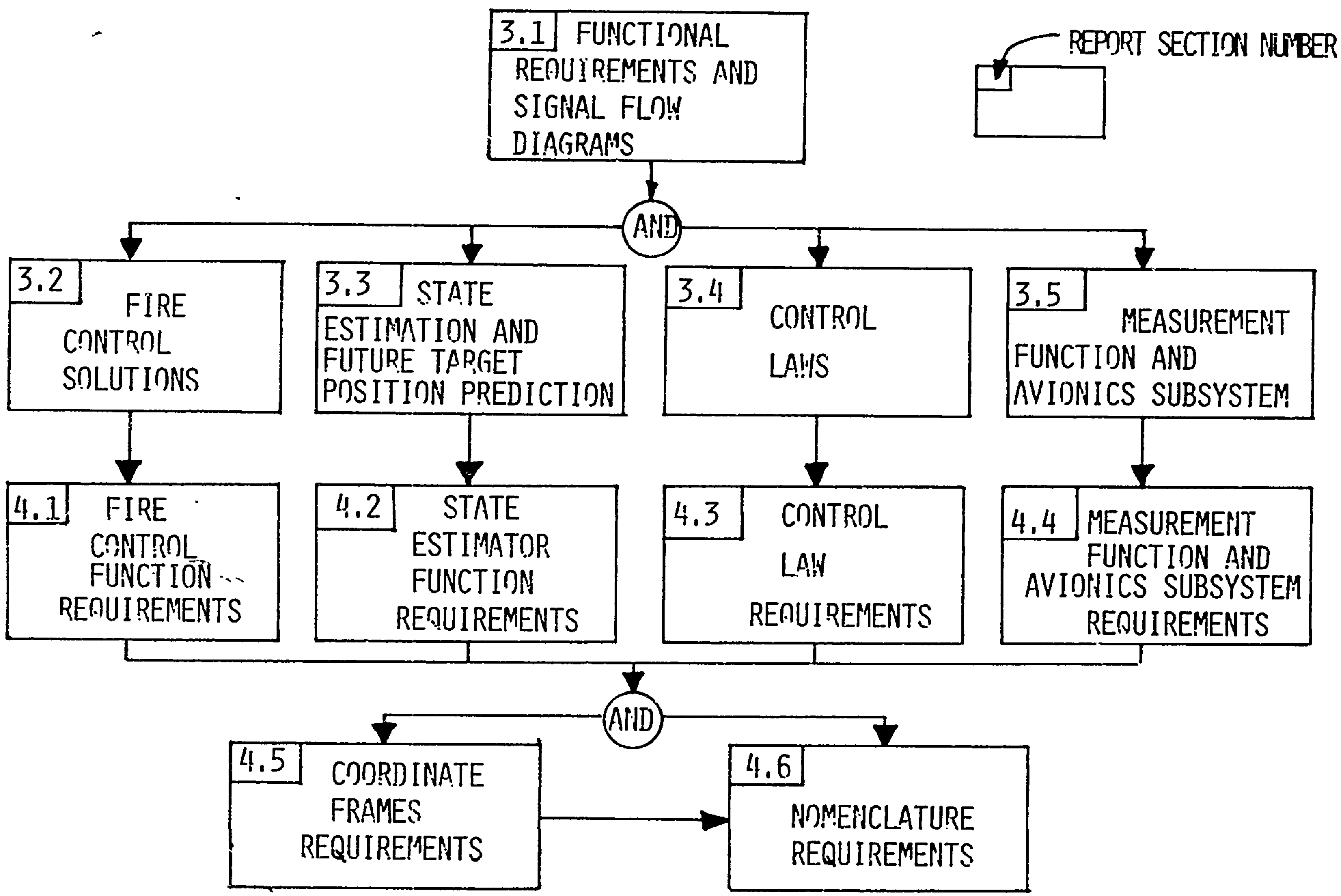


FIGURE 2. REQUIREMENTS DEVELOPMENT FLOW

3.0 GENERALIZED MECHANIZATION REQUIREMENTS ANALYSIS

The Generalized FIREFLY Mechanization is to be directly applicable to three basic weapon delivery modes; air-to-air gunnery (AAG), air-to-ground gunnery (AGG), and bombing. In addition, it is to have inherent compatibility with more conventional weapon delivery modes such as blind coordinate bombing, offset bombing, angle rate bombing, and all other types of Continuously Computed Release Point (CCRP) weapon delivery modes.

The AAG and AGG modes are director gunfire control modes in which the prediction of future target motion is made on the basis of data from a tracking sensor, such as a radar or electro-optical tracker. Based on range, range rate, angle, and angle rate measurements from the sensor or sensors combined with ownship data, estimates of target position, velocity and acceleration are formed in the estimator function of the Generalized Mechanization (GM). These target state estimates are used in the fire control function of the GM to form an extrapolated estimate of the target's position at some future time. Simultaneously, the fire control function computes the ballistic trajectory of the projectile out to one time-of-flight based on projectile aerodynamic forces and gravity.

The bombing mode is based on CCRP after target designation. Target designation can be accomplished either by lock-on with a tracking sensor or by overlaying a displayed target with a designation symbol and "marking" its position at the instant of designation. The target position vector after designation is computed either from tracker inputs or from aircraft velocity data. In general, this velocity data may be either air data or inertial velocities. The impact point vector and the predicted future target position vector are computed continuously in the CCRP modes. When the difference between these two vectors is reduced to an acceptable level, the selected weapon is released. The fire control system generates the control laws for fuselage aiming in the AAG and AGG modes and the steering command inputs for guiding the aircraft automatically to the weapon release point in a bombing mission. These control laws are applied to the flight control system through an interface (coupler) to achieve the desired aircraft response characteristics to command angular rates.

3.1 FUNCTIONAL RELATIONSHIPS AND SIGNAL FLOW DIAGRAMS

The overall signal flow diagram of the generalized FIREFLY control system mechanization is shown in Figure 3 The GM, shown in dotted lines, receives input

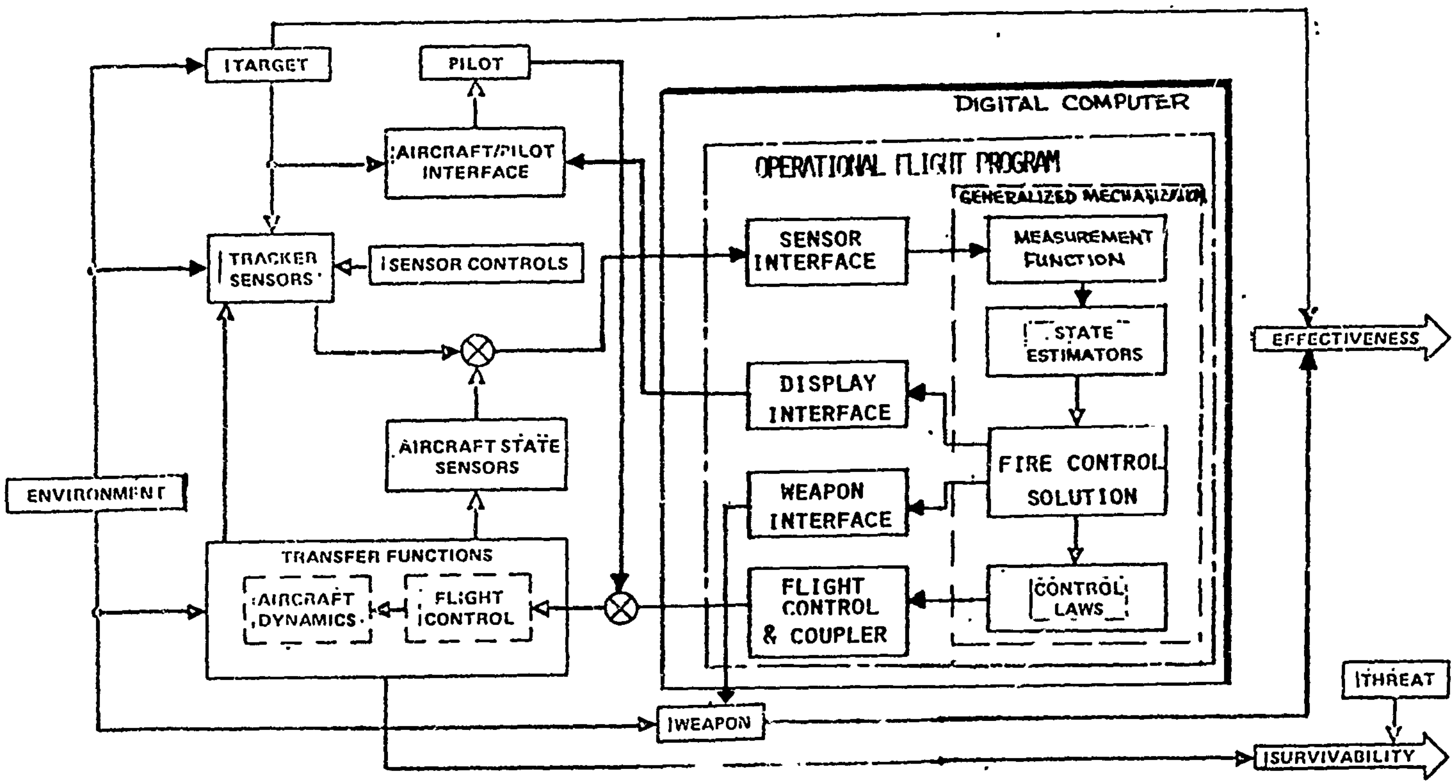


FIGURE 3. SIGNAL FLOW DIAGRAM OF FIREFLY IMPLEMENTATION

from the avionics subsystems (sensors) through an interface and generates the display information, aircraft steering control laws, and weapon release commands for various weapon delivery modes. The control laws in turn are applied through an interface (or coupler) to the aircraft flight control system, the display information is applied through an interface to the A/C pilot interface, and the weapon release commands are applied to the weapons through a weapons interface. These interfaces perform the operations or conversions required to ensure compatibility between the FIREFLY GM, the sensors, and the flight control system. These interfaces are contained within an Operational Flight Program (OFP) and are external to the GM.

Figures 4 through 9 show the input/output relationship for various subfunctions in the GM and the interdependence between the various computational units. The avionic subsystem outputs are processed through state estimators which compute the estimated quantities needed for the fire control solution. The ownship estimator shown in Figure 3-2 combines the body sensor outputs to generate smoothed estimates of aircraft position, inertial velocity and acceleration, angle of attack, and sideslip. The atmospheric estimator (Figure 5 combines the air data measurements with the ownship estimator outputs to obtain wind, aircraft velocity relative to air mass, air density, and altitude information. These estimators may range in complexity from simple mixing devices to more sophisticated Kalman filters depending upon the accuracy requirements in a specific application. The target state estimator shown in Figure 6 uses Kalman filtering algorithms to obtain accurate estimates of target range, relative velocity, and absolute target acceleration from ownship state estimates and line-of-sight (LOS) sensors.

Figures 7 and 8 show the functional relationships for the gunnery and bombing modes. The fire control solution generates the gun pointing commands, predicted future target position, miss distance, and other variables needed for the gunnery modes. The time-of-flight and the vectors $\overline{R}_B$ and $\overline{G}$ of the projectile ballistic which are also needed for the fire control solution are obtained from the ballistic algorithms.

The functional relationships for generating the bombing solution and the origin of various variables, such as measured, estimated, or known, are summarized in Table 1. The variables labelled as "known" are either fixed for a given aircraft or specified by the pilot to achieve the desired bombing accuracy.

The control laws and the flight control system interface is shown in Figure 9 for all three weapon delivery modes. There are basically two control laws that the GM must generate; one is the fuselage aiming commands for AAG and AGG and the

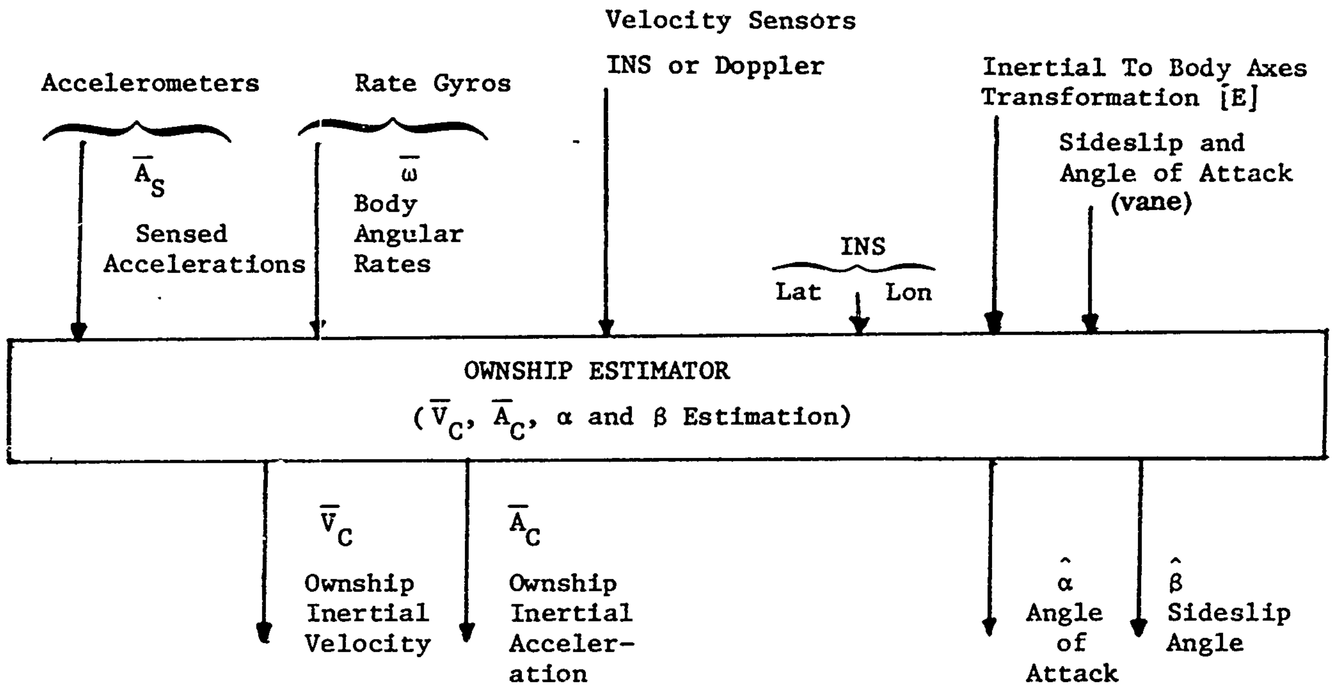


FIGURE 4. INPUT/OUTPUT REQUIREMENTS FOR THE OWNSHIP ESTIMATOR

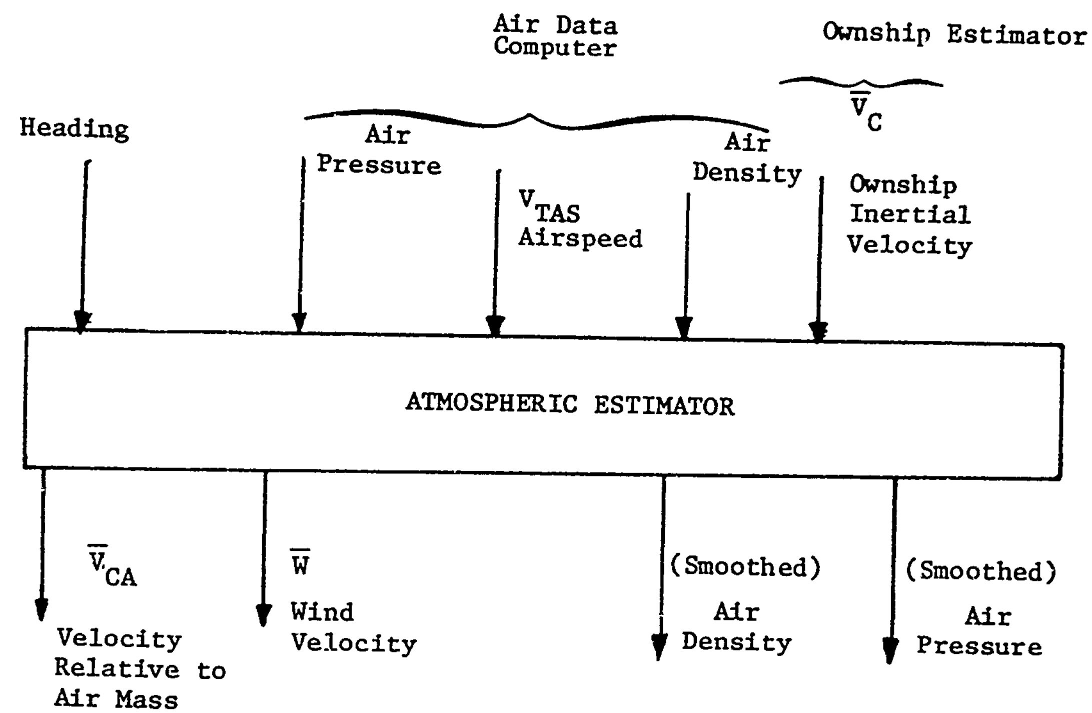
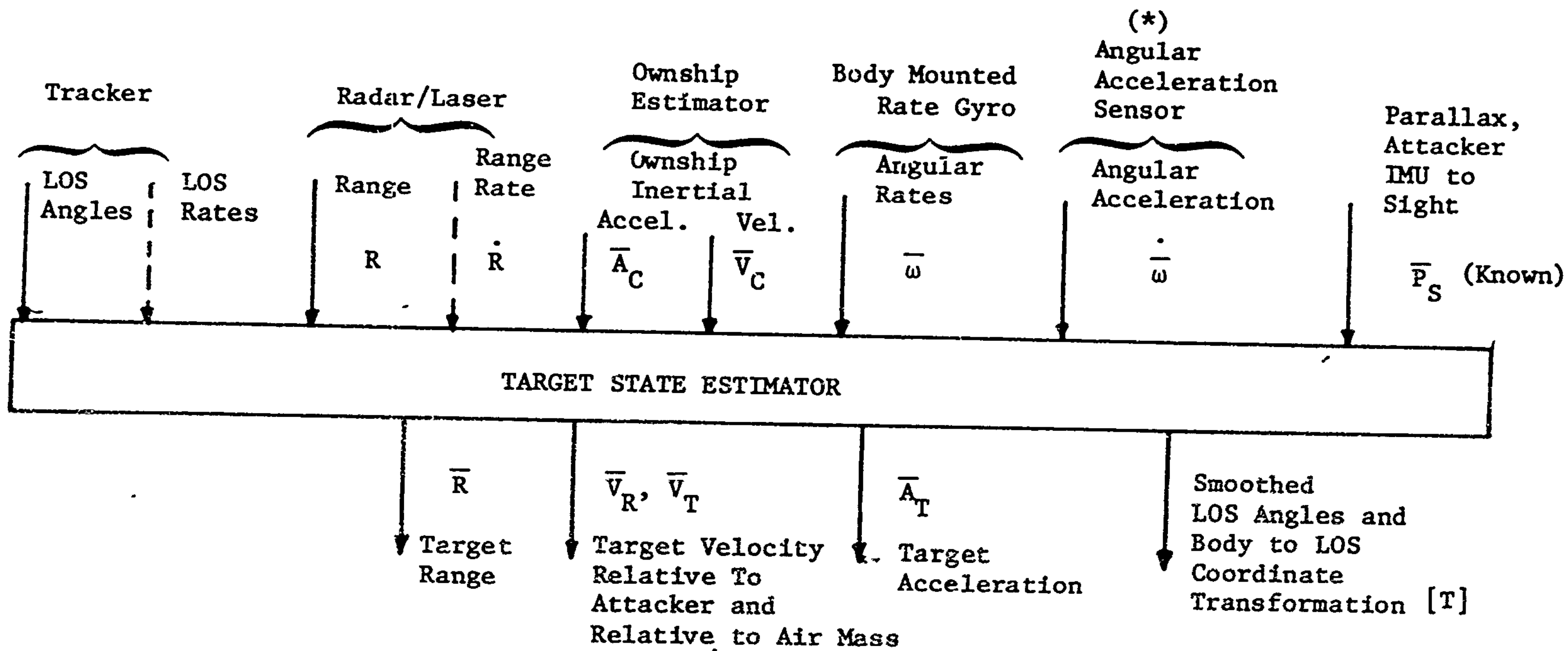


FIGURE 5. INPUT/OUTPUT REQUIREMENTS FOR THE ATMOSPHERIC ESTIMATOR



(*) Used to compute the incremental acceleration at the tracking sensor due to body rotations. This measurement/sensor can be omitted without introducing large errors.

FIGURE 6. INPUT/OUTPUT REQUIREMENTS FOR THE TARGET STATE ESTIMATOR

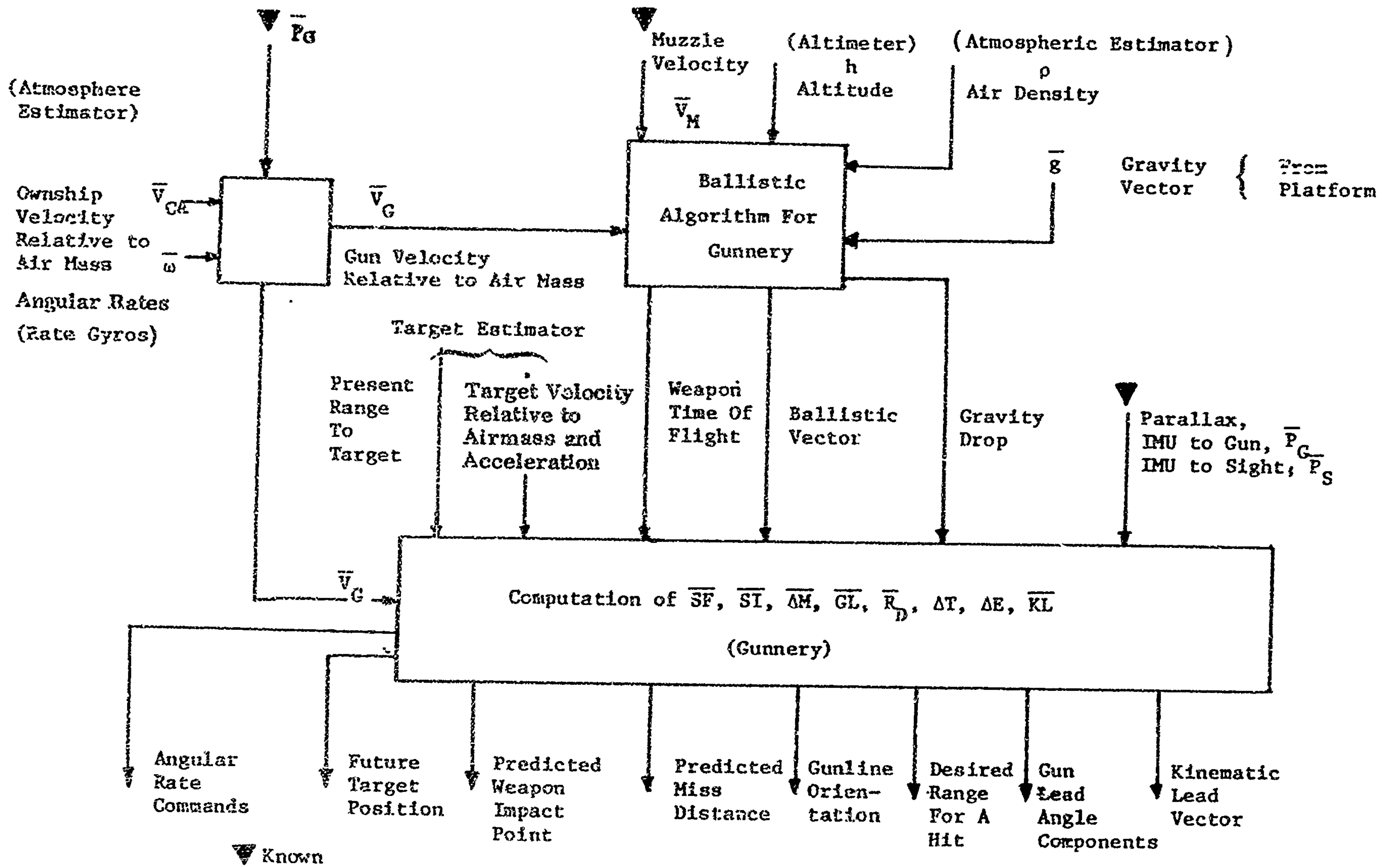
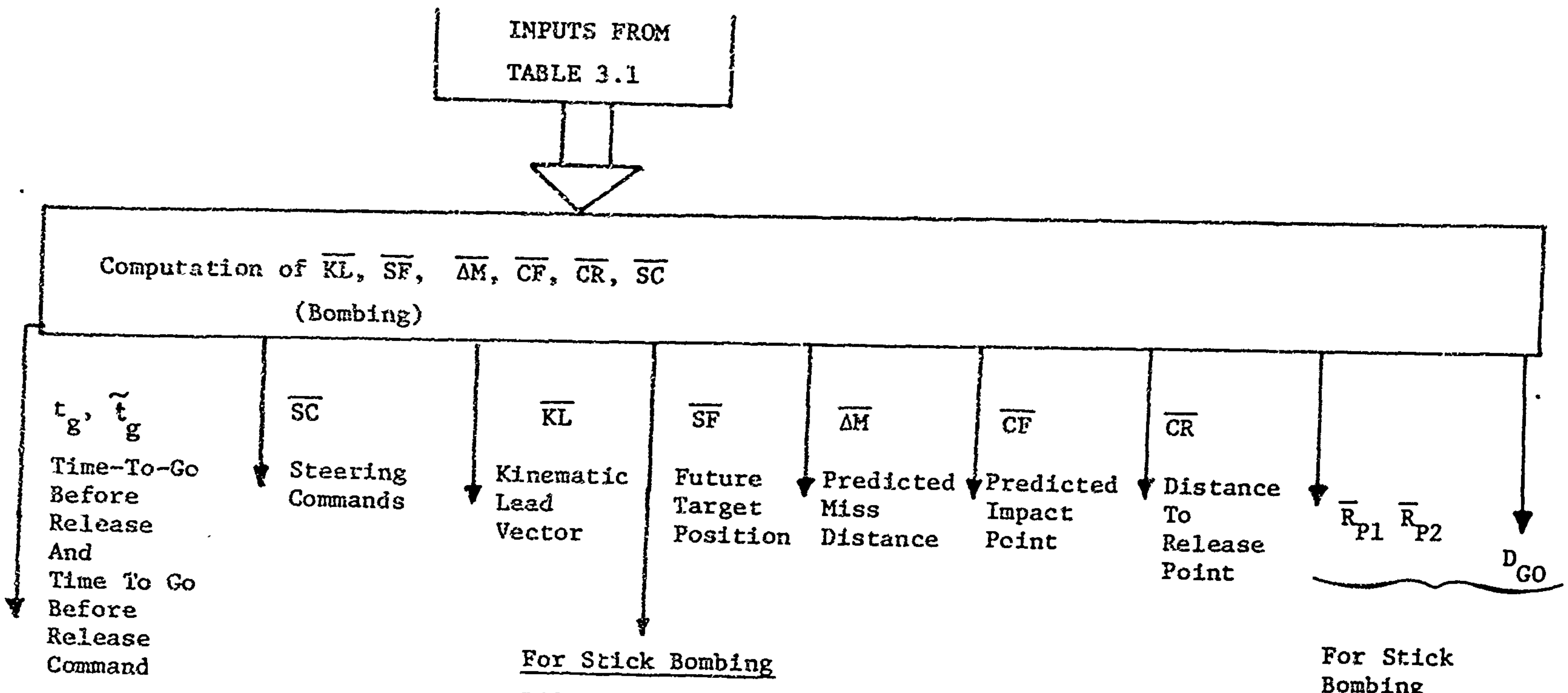


FIGURE 7. FUNCTIONAL REQUIREMENTS FOR THE GUNNERY FIRE CONTROL SOLUTION

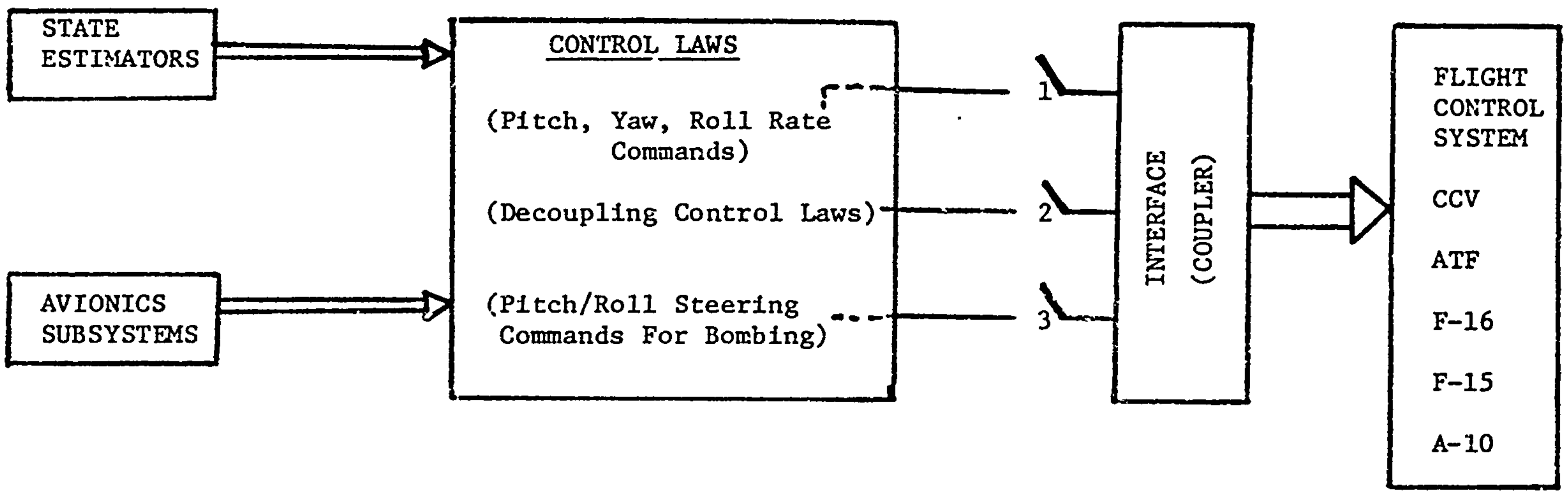


<u>For Stick Bombing</u>

DGO: Distance to go before turning

$\overline{R}_{P1}$, $\overline{R}_{P2}$: Range to points on the turning plane directly above endpoints of linear target.

FIGURE 8. FUNCTIONAL REQUIREMENTS FOR THE BOMBING FIRE CONTROL SOLUTION



Weapon Delivery Mode	Closed Switches
AAG	(1)
AGG	(1), (2)
Bombing	(3)

FIGURE 9. CONTROL LAW – FLIGHT CONTROL SYSTEM INTERFACE

TABLE 1. INPUTS REQUIRED FOR A BOMBING SOLUTION

SYMBOL	DESCRIPTION	ORIGIN
$\overline{V}_C$	Ownship inertial* velocity	Ownship state estimator
$\overline{A}_C$	Ownship inertial acceleration	Ownship state estimator
$\overline{V}_{CA}$	Ownship velocity relative to air	Atmosphere estimator
$\overline{W}$	Wind velocity relative to inertial coordinates	Atmosphere estimator
ρ	Air density	Atmosphere estimator
$\overline{V}_E$	Bomb ejection velocity	Known
$\overline{P}_S$	Sight parallax relative to body	
$\overline{P}_B$	Bomb (stores) parallax relative to body	Known
$\overline{D}_{of}$	Target position offset for stick or offset bombing	Known
τ	Rack delay	Known
$\overline{V}_R$	Relative target velocity	Target state estimator
$\overline{A}_T$	Inertial target acceleration	" " "
$\overline{R}$	Range to target	" " "
T_S, E_S	Azimuth and elevation angles of the LOS relative to body coordinates	" " "
$\overline{\omega}$	Ownship angular rate vector	Avionic Subsystem (sensors)
$[E]$	Transformation matrix from inertial to body axes	" " "
h_c	Altitude above target	" " (altimeter)
$\overline{R}_R$	Gravity drop along the local velocity vector relative to air.	Ballistic algorithm
$\overline{G}'$	Ballistic vector along the local vertical	" "
t_f	Time of flight	" "
DGO	Distance to go before turning (for stick bombing)	Computed
t_g	Time to go before bomb release	Computed

(*) Inertial quantities are defined in Section 3.3.1

other one is the aircraft steering commands for bombing. Additional feedbacks that are required to essentially decouple the lateral and longitudinal responses of the aircraft for the AGG mode are also shown.

The GM basically performs four functions; measurement function, state estimation function, fire control solution, and the generation of steering command signals (control laws). From a requirement dependency standpoint the flow is reversed as shown in Figure 10. Design considerations dictate the requirements for the fire control solution. From these requirements the state estimation and control law requirements are determined. Specific sensors on board an aircraft are adapted to the generalized state estimator and to the fire control solution through the measurement function. Similarly, the control law requirements are met on a specific aircraft (and a given flight control system) by proper design of a specialized coupler.

The analysis of the requirements for each of the four basic functions will be contained in the following sections based on the GM requirements for AAG, AGG, and bombing delivery modes.

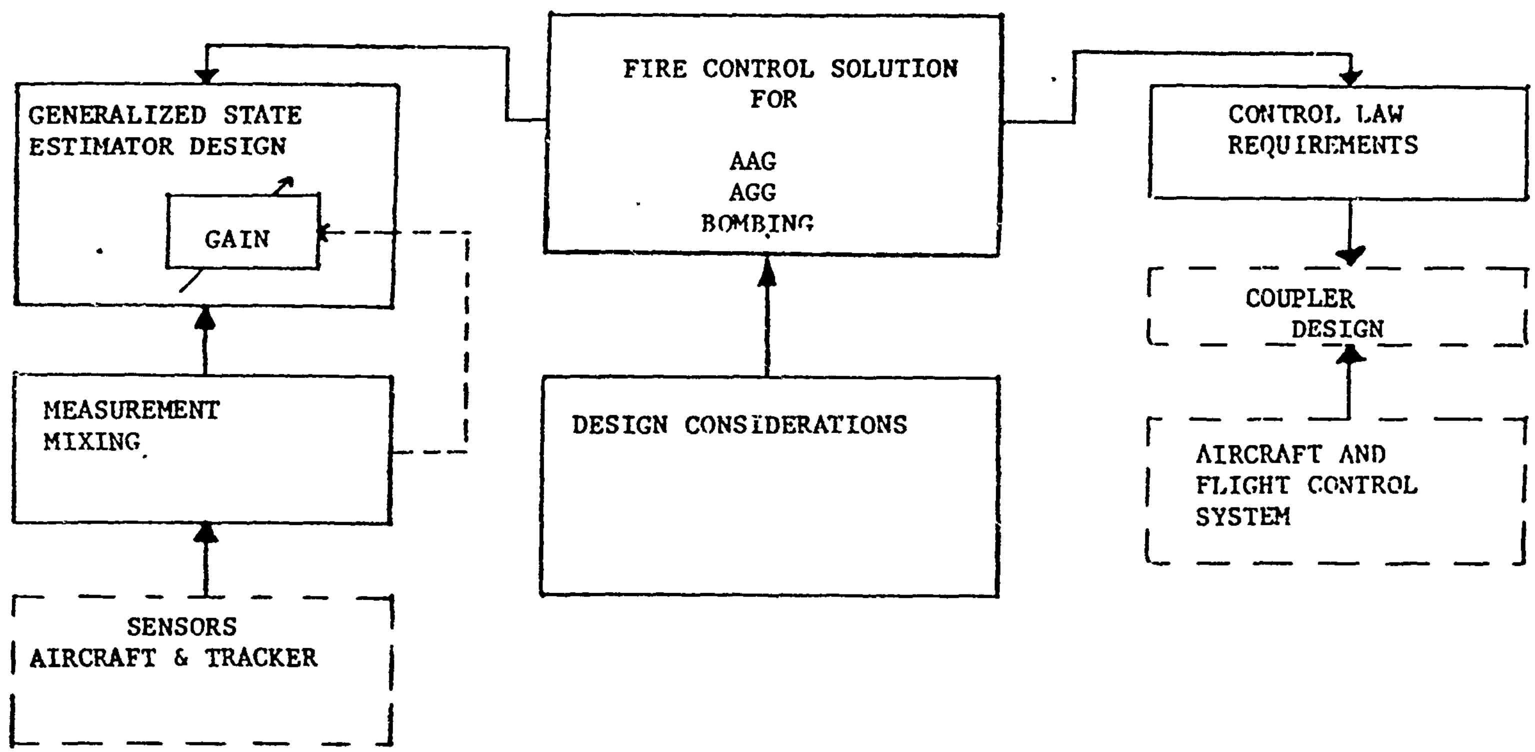


FIGURE 10. FUNCTIONAL DEPENDENCY FLOW OF THE GENERALIZED MECHANIZATION

3.2 FIRE CONTROL SOLUTIONS

Several refinements and improvements for a generalized fire control solution were discovered during the FIREFLY familiarization phase. There refinements are imposed as requirements on the generalized FIREFLY mechanization design, summarized in Section 4.

This section includes a discussion on ballistic algorithms (Section 3.2.1), time of flight computation (Sections 3.2.3 and 3.2.5), Fire control solutions for AAG and AGG modes (Section 3.2.2), for bombing (Section 3.2.1) and for stick bombing (Section 3.2.6).

3.2.1 Requirements Analysis For Ballistic Algorithms

This section deals with the definition of the requirements of air-to-air (A/A) and air-to-ground (A/G) ballistic algorithms and the potential utilization of some of these in FIREFLY. Section 3.2.1.1 discusses the general requirements for A/G weapon delivery, followed by a comparison of the relative merits of closed form expressions vs. numerical integration ballistic formulations. The requirements for A/A fire control are discussed in Section 3.2.1.2.

3.2.1.1 A/G Ballistic Algorithms

For the purpose of bombing, AGG and rocketry, there are certain requirements on the aircraft in order to accomplish effective weapon delivery. The aircraft sensors and/or estimators must be able to measure or estimate the relative target position and velocity, the aircraft velocity in the air mass, and the gravity vector. In addition, in order to predict where the weapon will fall, there exists a requirement to have available in the airborne fire control computer a ballistic algorithm for the following weapon types: low drag bombs, retarded bombs, cluster weapons, gun projectiles, and unguided rockets. These weapons have in common the characteristics that they are all ballistic projectiles, that is, that once released from the aircraft, the only forces which act on the weapon are the aerodynamic forces and the force due to gravity. Aerodynamic forces usually include drag, velocity jump and windage jump efforts. (Note that for the case of unguided rockets, the weapon can be considered a ballistic projectile only after burnout).

In the past, attempts were made to provide a ballistic algorithm in closed-form by formulating a simplified drag model in such a way that the differential equation of motion is solvable by analytical methods. In addition, these approximate solutions may be modified by empirically-derived functions that are intended to compensate for some of the simplifications in the drag model, in order to provide reasonable accuracy over a specified release envelope.

The other method of providing an airborne ballistic algorithm is that of numerical integration. While this method is advantageous from the point of view of being very accurate and flexible, it is not directly amenable to the type of fire control solution sought in the FIREFLY algorithm. Adaptation of numerical integration methods would require an iterative solution which may take large amounts of computer time (up to a few seconds) to complete the calculations. However, it is possible to modify the numerical integration technique for near-real-time solution in an airborne computer. The premium example of the numerical integration technique of computing the weapon trajectory in an airborne ballistic algorithm is the China Lake Algorithm.

The following is a brief discussion of the relative advantages of the closed-form and numerical integration ballistic algorithm techniques.

1. Both types of algorithms are nearly equal in accuracy when a single weapon is considered in the "heart of the delivery envelope." However, under more severe delivery conditions the numerical integration technique is superior to the closed-form method, due to its generality, because the empirical modifying functions employed in the closed-form method are derived only for a particular region of the delivery envelope.

2. The numerical integration method is more flexible when a new weapon is to be added to the algorithm; all that need be done is to fit the aerodynamic functions of that weapon into the format of the algorithm. On the other hand, for the closed-form method an entirely new function must be derived for each new weapon, thus leading to larger memory requirements.

3. The one primary advantage which the closed-form method has over the numerical integration method is that of computational time. While the numerical integration method is more accurate over a larger delivery envelope, and is a more flexible algorithm than the closed-form method, the larger number of calculations required for the numerical integration makes the total computational time greater than that for the closed-form method.

In conclusion, it is apparent that both methods have their own merits, and that when when only a very few weapons are included in the algorithm the two methods are approximately equal in value. However, when there are many weapons of different types in the aircraft weapon repertoire, the numerical integration method is most likely the more effective of the two because of its greater flexibility, accuracy, and the less memory space required. The cost of memory space, however, is unlikely to be a determining factor since smaller and faster computers are continuously being developed.

3.2.1.2 A/A Ballistic Algorithms

Just as in the case of A/G weapon delivery, there exists a requirement in AAG to have a ballistic algorithm available in the fire control computer. Based upon the knowledge and experience gained with A/G ballistic algorithms, it is evident that an A/A numerical integration ballistic algorithm would probably yield greater accuracy than a fitted ballistic algorithm in closed-form. At present there are no A/A ballistic algorithms which make use of the numerical integration technique similar to that of the China Lake Algorithm; there are numerous closed-form ballistic formulations for AAG, each of which makes different simplifying assumptions according to which gun-sight lead angle computation the ballistic equations require. The disadvantages present in A/G closed-form ballistic algorithms -- namely, the large memory requirements brought about by a large number of weapon types, and the inaccuracies which occur when releases are made outside of the "heart of the delivery envelope" -- are somewhat alleviated in the A/A case. Memory requirements would be smaller because the number of different weapons would be small for A/A applications. Also, in A/A encounters the ranges involved are not as large, and the analog of the "release envelope" is not as severely large as in A/G weapon delivery. All of this puts the closed-form ballistic algorithms on a par with the numerical integration technique.

In summary, even though the numerical integration and closed-form ballistic algorithms are of approximately the same value, from the point of view of commonality with the A/G ballistic algorithm, the numerical integration method is most likely the better of the two methods. However, caution must be exercised so that update rate requirements imposed on the ballistic algorithms by other fire control functions are not violated. A numerical integration scheme might be made to compute time-of-flight and range more rapidly than the China Lake Algorithm since the weapon trajectory is relatively straight and ranges are generally small.

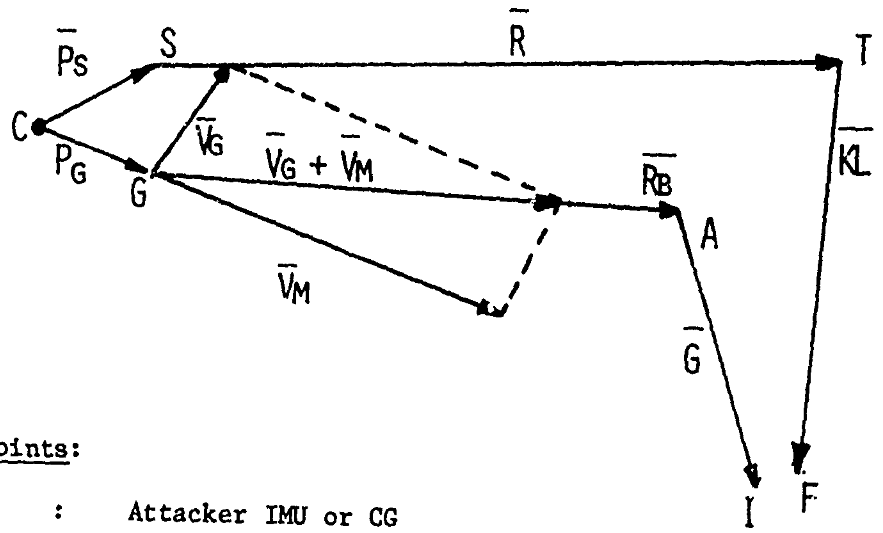
3.2.2 Fire Control System For Gunnery

The problem of formulating a fire control solution for gunnery modes (and also for bombing) involves predicting the target position one time-of-flight (TOF) in the future and simultaneously computing the weapon ballistic trajectory out to one TOF. For consistency the estimation/prediction problem and the ballistic trajectory problem will be formulated in air mass coordinates.

Various vectors which enter into the fire control solution for the (AAG, AGG) gunnery modes are illustrated in Figure 11. The projectile ballistic vector $\overline{GI}$ is broken down into components $\overline{GA} = \overline{R}_B$ and $\overline{AI} = \overline{G}$, such that $\overline{R}_B$ is along the total initial air mass velocity vector, $\overline{V}_M + \overline{V}_G$, and $\overline{G}$ is along the local vertical, where $\overline{V}_M$ is the muzzle velocity vector (projectile velocity relative to attacker) and $\overline{V}_G$ is the gun velocity relative to the air mass. Both vectors $\overline{R}_B$ and $\overline{G}$ include the effect of drag which tends to oppose the air velocity vector along the projectile trajectory. While the projectile travels from point G to point I in air mass coordinates, the target moves from point T to point F, where the vector $\overline{TF} = \overline{KL}$ is the kinematic lead vector relative to the air mass. A hit occurs when point I coincides with point F, or when the vectors $\overline{GI}$ and $\overline{GF}$ become equal, that is:

$$\overline{GI} = \overline{R}_B + \overline{G} = -\overline{P}_G + \overline{P}_S + \overline{R} + \overline{KL} = \overline{GF} \qquad (3\text{-}4)$$

This is the fundamental relationship used in the derivation of the fire control solution and the aircraft steering command signals, based on Figure 11. This expression is valid for both the AAG and AGG modes and provides commonality for the gunnery modes. Note that in the AGG mode the target actually travels relative to earth, however for consistency $\overline{KL}$ represents the motion relative to the air mass.



Points:

C : Attacker IMU or CG

S : Attacker Sight

G : Attacker Gun

T : Present target position

F : Future target position in air mass coordinates

A : Aim point

I : Weapon impact point

Vectors

$\overline{P}_S$: Parallax, attacker IMU to sight

$\overline{P}_G$: Parallax, attacker IMU to gun

$\overline{R}$: Present range to target

$\overline{KL}$: Kinematic lead vector relative to the air mass

$\overline{G}$: Gravity drop

$\overline{R}_B$: Weapon travel along total velocity vector relative to the air mass $\overline{V}_M+\overline{V}_G$

$\overline{V}_G$: Attacker velocity relative to the air mass at the gun station

$\overline{V}_M$: Muzzle velocity along gunline (projectile velocity relative to attacker)

FIGURE 11. VECTORS ASSOCIATED WITH AIR-TO-AIR FIRE CONTROL MODE

Future Target Position relative to sight (in air mass coordinates)

$$\overline{SF} = \overline{R} + \overline{KL} \tag{3-5}$$

Predicted Weapon Impact Point relative to sight (in air mass coordinates)

$$\overline{SI} = \overline{R}_B + \overline{G} + \overline{P}_G - \overline{P}_S \tag{3-6}$$

Predicted Miss Distance is given by ΔM relative to sight

$$\Delta M = \sqrt{\Delta M_1{}^2 + \Delta M_2{}^2 + \Delta M_3{}^2} \tag{3-7}$$

where ΔM_1, ΔM_2 and ΔM_3 are the components of vector $\overline{\Delta M}$ in arbitrary coordinates

$$\overline{\Delta M} = \begin{bmatrix} \Delta M_1 \\ \Delta M_2 \\ \Delta M_3 \end{bmatrix} = -\overline{P}_G + \overline{P}_S + \overline{R} + \overline{KL} - \overline{G} - \overline{R}_B = \overline{S}_F - \overline{SI} \tag{3-8}$$

Gunline Direction Cosines for a Hit

The orientation of the gunline is defined by the muzzle velocity vector $\overline{V}_M$. Defining the distance loss due to drag as $\overline{DB}_1 = \overline{R}_B - t_f\ (\overline{V}_M + \overline{V}_G)$ and solving for $\overline{V}_M t_f$ from Equation 3-4 yields:

$$\overline{GL} = \overline{V}_M t_f = -\overline{P}_G + \overline{P}_S + \overline{R} + \overline{KL} - \overline{DB}_1 - \overline{G} - t_f\ \overline{V}_G \tag{3-9}$$

The gunline direction cosines are then given by

$$\begin{bmatrix} GL_1/|\overline{GL}| \\ GL_2/|\overline{GL}| \\ GL_3/|\overline{GL}| \end{bmatrix} \tag{3-10}$$

where $|\overline{GL}|$ is the norm and GL_1, GL_2, and GL_3 are the components of the vector $\overline{GL}$ in arbitrary coordinates.

Desired Range for a Hit is by definition the current range which satisfies the condition for a hit in Equation 3-4. Solving for $\overline{R}$ and designating the result by $\overline{R}_D$ yields:

$$\overline{R}_D = \overline{R}_B + \overline{G} + \overline{P}_G - \overline{P}_S - \overline{KL} \tag{3-11}$$

Gun Lead Angle is the angle between the desired LOS (or vector $\overline{R}_D$) and the gunline vector $\overline{V}_M t_f$. The direction cosines of this angle can be obtained by resolving the gunline vector $\overline{V}_M t_f$ in the LOS or HUD coordinates (GL_1, GL_2, GL_3) and computing the direction cosines as in Equation (3-10). As an alternative procedure, the azimuth (ΔT) and elevation (ΔE) angles of the gun lead angle relative to arbitrary (body, gun, LOS or HUD) coordinates can be obtained as follows:

$$\begin{aligned} \Delta T &= \tan^{-1} \frac{R_{D_2}}{R_{D_1}} - \tan^{-1} \frac{GL_2}{GL_1} \\ \Delta E &= -\sin^{-1} \frac{R_{D_3}}{|\overline{R}_D|} + \sin^{-1} \frac{GL_3}{|\overline{GL}|} \end{aligned} \tag{3-12}$$

where R_{D_1}, R_{D_2} R_{D_3} are the components of the desired range vector $\overline{R}_D$ and GL_1, GL_2, GL_3 the components of the gunline in arbitrary coordinates.

3.2.3 Time-of-Flight Computation for AAG and AGG

The purpose of the fire control solution for AAG and AGG is to obtain the weapon TOF and the aiming vector direction cosines that satisfy the condition for a hit in Equation (3-4). The solution method for the TOF computation depends on whether closed-form expressions or numerical integration methods are used for the weapon ballistics. The functional requirements for each case will be obtained below.

3.2.3.1 TOF Computation Using Closed-Form Ballistic Equations

The TOF is computed from the scalar equation resulting from the projection of Equation 3-4 onto a convenient axis, such as the LOS. Since the vectors $\overline{R}_B$, $\overline{G}$ and $\overline{KL}$ depend on the TOF, t_f must be solved iteratively from the resulting equations until the error ϵ becomes arbitrarily small.

$$\varepsilon = R_{B_1} + G_1 + P_{G_1} - P_{S_1} - R_1 - KL_1 \tag{3-13}$$

where subscript (1) denotes the vector component along the arbitrary axis. The Newton-Raphson algorithm for solving t_f is:

$$(t_f)_{n+1} = (t_f)_n - \frac{(\varepsilon)_n}{\left(\frac{\partial \varepsilon}{\partial t_f}\right)_n}$$

where

$$\frac{\partial \varepsilon}{\partial t_f} = \frac{\partial R_{B_1}}{\partial t_f} + \frac{\partial G_1}{\partial t_f} - \frac{\partial KL_1}{\partial t_f}. \qquad (3\text{-}14)$$

3.2.3.2 TOF Computation Using Numerical Integration Methods

China Lake algorithms can be modified to converge on slant range instead of altitude for the numerical integration of weapon ballistic equations. This procedure would be equivalent to the closed-form iteration along the LOS proposed in Section 3.2.3.1.

The modified China Lake algorithm would compute the weapon TOF and the weapon ground range from given initial velocity $\overline{V}_M + \overline{V}_G$ and slant range, as shown in Figure 12. From the geometry in this figure the vectors $\overline{R}_B$ and $\overline{G}$ used in the fire control solution are obtained as follows:

$$\overline{R}_B = \frac{\overline{V}_M + \overline{V}_G}{|\overline{V}_M + \overline{V}_G|} \cdot \frac{R_G}{\cos}$$

$$\overline{G} = \left(\sqrt{R_S^2 - R_G^2} + R_G \tan\gamma\right) \overline{Z} \qquad (3\text{-}15)$$

where Z is a unit vector along the local vertical, R_S is slant range and γ is the elevation angle of the total velocity vector, $\overline{V}_M + \overline{V}_G$ measured positive counterclockwise.

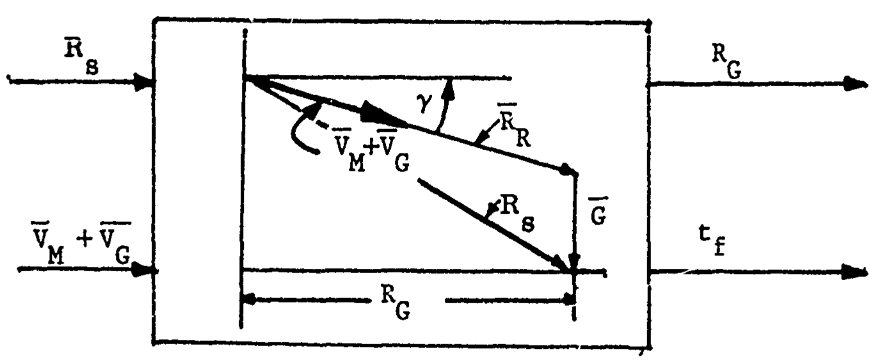


FIGURE 12. MODIFIED CHINA LAKE NUMERICAL INTEGRATION ALGORITHM FOR AAG AND AGG

An iterative solution can be set up to adapt the China Lake algorithm to FIREFLY gunnery solutions as shown in Figure 13. In this diagram initial values for slant range (R_S) and velocity vector ($\overline{V}_M + \overline{V}_G$) are assumed. Weapon ballistic equations are integrated numerically to obtain t_f and R_G. Knowing t_f the kinematic lead vector and the miss distance are computed, and the initial slant range R_S is adjusted accordingly in an iterative manner until the miss distance is reduced to an acceptable level.

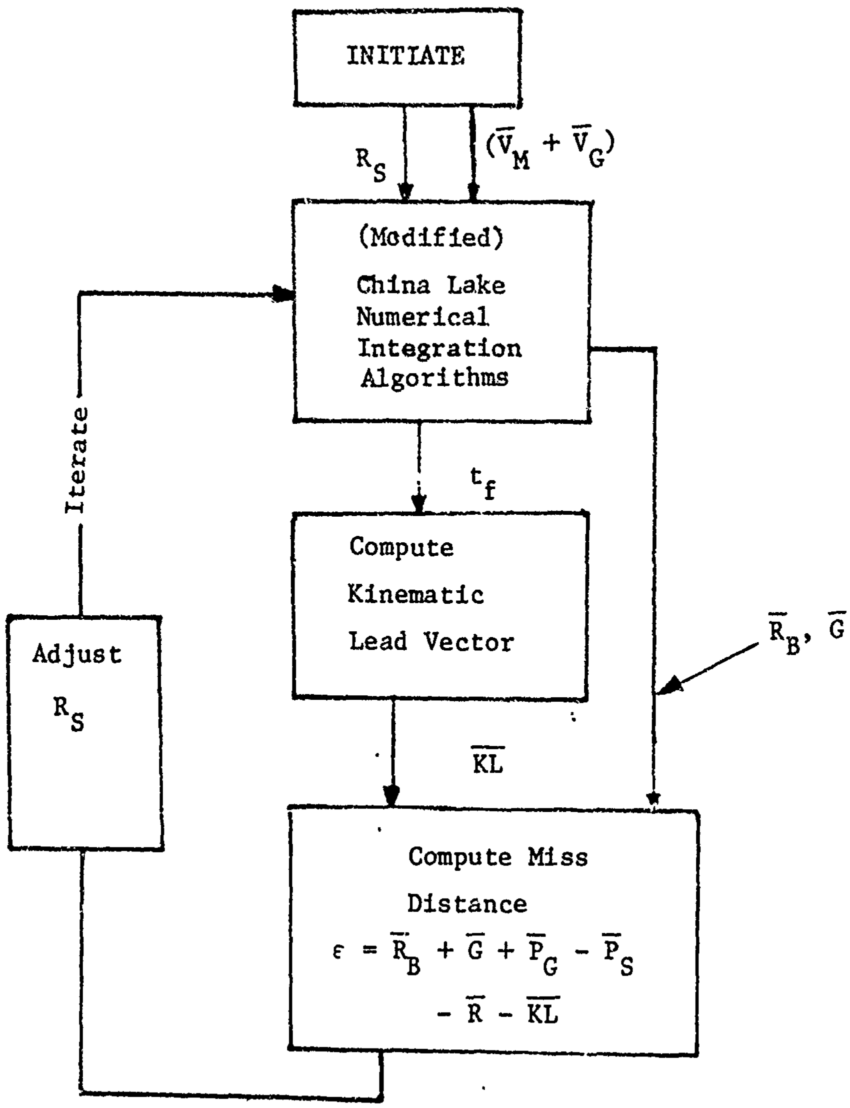


FIGURE 13. TIME OF FLIGHT COMPUTATION USING A MODIFIED (CHINA LAKE) NUMERICAL INTEGRATION ALGORITHM

3.2.4 Fire Control System for Bombing

FIREFLY bombing algorithms allow for a maneuvering approach to bomb release in order to enhance survivability to enemy (AAA or SAM) defenses while maintaining a high level of offensive weapon delivery accuracy. The maneuver consists of a circular flight trajectory on a nonhorizontal turning plane. The release point along this trajectory is computed continuously (CCRP), by assuming constant turn rate and constant ownship velocity relative to the air mass.

Figure 14 shows the turning plane geometry for bombing. The turn is initiated at point C and the bomb is released at point R. Point C is also the point where the target is sighted, and the CCRP computation is performed. From point C to point R the aircraft flies a circular trajectory relative to the air mass. The velocity vectors relative to the air mass at points C and R are tangent to the circle; hence, the following fundamental relationship holds for FIREFLY bombing.

$$R_P \sin\lambda = \frac{R_P^{\,2} - R_R^{\,2}}{2V_{CA}}\,\omega \tag{3-16}$$

In vector form this relationship becomes

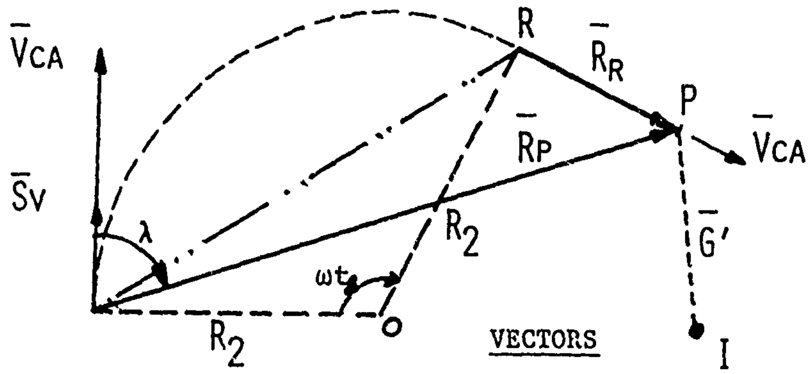
$$\overline{S}_V \times \overline{R}_P = \frac{R_P^{\,2} - R_R^{\,2}}{2V_{CA}}\,\overline{\omega} \tag{3-17}$$

The vector diagram used for computing the desired weapon impact point (F) is shown in Figure 15. From this figure the vector $\overline{CF}$ is given by:

$$\overline{CF} = \overline{P}_S + \overline{R} + \overline{KL} + \overline{D}_{of} \tag{3-18}$$

The vector diagram at the release point is shown in Figure 16, wherein the combined effect of bomb ejection velocity ($\overline{V}_E$), wind velocity $\overline{W}$ and parallax ($\overline{P}_B$ + $\overline{\omega} \times \overline{P}_B\, t_f$) is represented as an impact point correction (I'I) in order to allow the fundamental relationship in Equations (3-16 and 17) to be used for the generalized bombing solution. Otherwise a point P, directly above the weapon impact point on the turning plane which lies along the velocity vector $\overline{V}_{CA}$, cannot be defined. In general, however, the incremental bomb initial velocity $\overline{V}_E + \overline{\omega} \times \overline{P}_B$ will affect the aerodynamic forces acting on the bomb. But, this effect is negligibly small.

CIRCULAR FLIGHT PATH



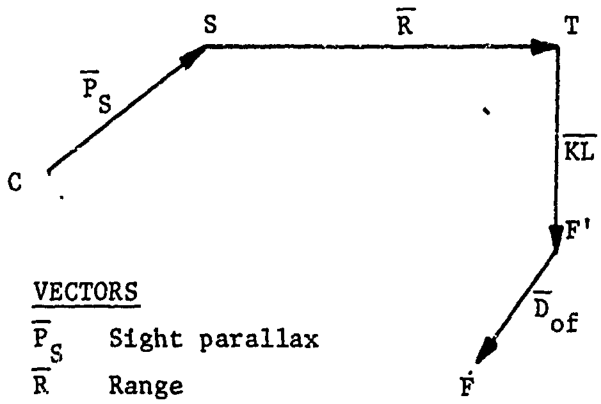
POINTS

O	Origin of turning circle
C	IMU location (or aircraft CG) at turn initiation
R	Bomb release point
P	Point on turning plane directly above weapon impact point
I	Weapon impact point

VECTORS

$\overline{V}_{CA}$	Ownship velocity relative to air
$\overline{S}_V$	Unit vector along $\overline{V}_{CA}$
$\overline{R}_P$	Vector from point C to point P
$\overline{R}_R$	Weapon travel along $\overline{V}_{CA}$ from release to point P.
$\overline{G}'$	Vertical drop of weapon
R_2	Radius of turning circle
λ	Angle between $\overline{V}_{CA}$ and $\overline{R}_P$

FIGURE 14. TURNING PLANE GEOMETRY FOR BOMBING



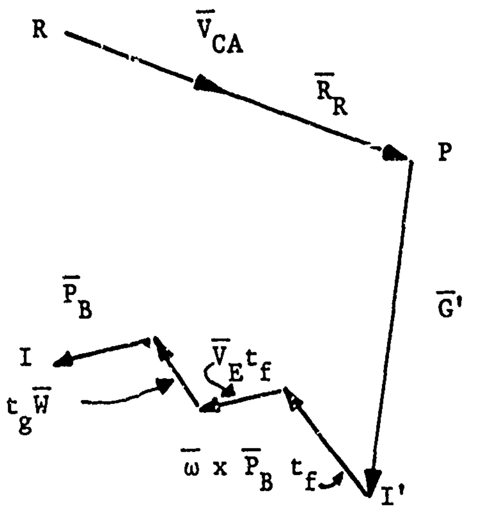
VECTORS

$\overline{P}_S$	Sight parallax
$\overline{R}$	Range
$\overline{KL}$	Kinematic lead vector relative to the air mass
$\overline{D}_{of}$	Target position offset

POINTS

C	IMU location at turn initiation
S	Target tracking sensor
T	Present target position
F'	Future target position relative to the air mass
F	Desired weapon impact point relative to the air mass

FIGURE 15. VECTOR DIAGRAM AT TURN INITIATION



VECTORS

$\overline{W}$ Wind velocity relative to inertial coordinates

$\overline{P}_B$ Bomb parallax

$\overline{V}_B$ Ownship velocity at bomb location

$\overline{V}_E$ Bomb ejection velocity relative to body

$\overline{V}_{CA}$, $\overline{R}_R$, $\overline{G}'$ Defined above.

FIGURE 16. VECTOR DIAGRAM FOR BOMB RELEASE POINT COMPUTATION

The condition for a hit is satisfied when the desired impact point (point F in Figure 15 coincides with the actual impact point (point I in Figure 16.) From this condition the vector $\overline{CP} = \overline{R}_P$ defined in Figure 3-12 is obtained as follows.

$$\overline{R}_P = \overline{P}_S + \overline{R} + \overline{KL} + \overline{D}_{of} - \overline{W}\, t_g - (\overline{V}_E + \overline{\omega} \times \overline{P}_B) \cdot t_f - \overline{G}' - \overline{P}_B{}^* \qquad (3\text{-}19)$$

The angle subtended by the circular path CR is ωt_g, hence from the geometry in Figure 14 the time to go before release, t_g, becomes:

$$t_g = \frac{2}{\omega} \sin^{-1} \left(\frac{|\overline{R}_P - \overline{R}_R|}{2\, V_{CA}} \right) \qquad (3\text{-}20)$$

where $|\overline{R}_P - \overline{R}_R|$ denotes the length of vector $\overline{CR}$.

Fire Control Parameters

Various parameters which are needed for the bombing solution can now be expressed as a function of the vectors defined above.

(*) Note that if $\overline{KL}$ is relative to inertial coordinates $\overline{W}t_i$ should be substituted in place of $\overline{W}t_g$.

Weapon Release Point, or distance to go to bomb release

$$\overline{C}_R = \overline{R}_P - \overline{R}_R \tag{3-21}$$

Future (offset) Target Position relative to tracking sensor location S.

$$\overline{SF} = \overline{R} + \overline{KL} + \overline{D}_{of} \tag{3-22}$$

Predicted Weapon Impact Point relative to point S.

$$\overline{SI} = \overline{R}_P - \overline{P}_S + \overline{G}' + (\overline{V}_E + \overline{\omega} \times \overline{P}_B) \cdot t_f + \overline{P}_B + \overline{W}t_g \tag{3-23}$$

Predicted Miss Distance is

$$\Delta M = \sqrt{\Delta M_1^{\,2} + \Delta M_2^{\,2} + \Delta M_3^{\,2}} \tag{3-24}$$

where ΔM_1, ΔM_2, ΔM_3 are the components of the vector $\overline{\Delta M}$ in arbitrary coordinates,

$$\begin{aligned}\overline{\Delta M} = \overline{SF} - \overline{SI} &= \overline{R} + \overline{KL} + \overline{D}_{of} - \overline{R}_P + \overline{P}_S - \overline{G}' - \overline{W}t_g \\ &- (\overline{V}_E + \overline{\omega} \times \overline{P}_B) \cdot t_f - \overline{P}_B\end{aligned} \tag{3-25}$$

Condition for a Hit is

$$\Delta M = 0 \text{ or } \overline{SF} = \overline{SI} \tag{3-26}$$

Time to Bomb Release Command

The equations above are derived relative to the true release point R. Because of the rack delay (τ) the bomb release must be initiated τ seconds before reaching point R or $t_g - \tau$ seconds after passing through point C, hence

$$\begin{array}{l}\text{Time to go}\\ \text{before bomb release}\\ \text{command}\end{array} = \frac{2}{\omega} \sin^{-1}\left(\frac{|\overline{R}_P - \overline{R}_R|}{2\, V_{CA}}\right) - \tau \tag{3-27}$$

3.2.5 Time-of-Flight Computation for the Bombing Solution

The vectors defined above depend on the TOF and hence the TOF must be computed in order to complete the fire control solutions and determine the release point along the turning circle. The TOF and the control laws are derived from the fundamental relationship for FIREFLY bombing in Equation 3-17. The control law adjusts the inclination of the turning plane (the direction of $\bar{\omega}$) while the TOF is computed such that the magnitudes of the vectors in Equation 3-17 are made equal.

3.2.5.1 TOF Computation Using Closed-Form Ballistics

The magnitude equality in Equation 3-17 is satisfied by nulling the error ϵ

$$\epsilon = R_{D2} - R_{D1}$$

where

$$\varepsilon = R_{D2} - R_{D1}$$

$$R_{D1} = \frac{R_P^{\,2} - R_R^{\,2}}{2\,V_{CA}}\,\omega = \frac{\omega}{2\,V_{CA}}\left[\bar{R}_P^{\,T}\,\bar{R}_P - \bar{R}_R^{\,T}\,\bar{R}_R\right] * \qquad (3\text{-}28)$$

$$R_{D2} = |S_V \times R_P| = \sqrt{C_{P1}^{\,2} + C_{P2}^{\,2} + C_{P3}^{\,2}} = |\bar{C}_P|$$

Vector notation is used to derive expressions for the partial derivatives of $\bar{R}_P$ and $\bar{R}_R$ with respect to t_f. Hence, the formulation presented here is more general than the Firefly II formulation and does not require simplifying assumptions, similar to those in the FIREFLY II report, to be made in order to obtain the desired expressions.

All quantities in Equation 3-28 are nonlinear functions of the TOF, hence t_f must be solved iteratively from these equations. The Newton-Raphson algorithm for solving t_f is given

$$(t_f)_{n+1} = (t_f)_n - \frac{(\varepsilon)_n}{\left(\dfrac{\partial\varepsilon}{\partial t_f}\right)_n} \qquad (3\text{-}29)$$

where

$$\frac{\partial\varepsilon}{\partial t_f} = \frac{\partial R_{D2}}{\partial t_f} - \frac{\partial R_{D1}}{\partial t_f}$$

(*) Superscript T denotes vector transposition.

3.2.5.2 TOF Computation Using Numerical Integration

A particularly useful method for computing the weapon ballistic trajectory is to integrate the ballistic equations numerically from bomb release to impact by using the China Lake algorithms. These algorithms provide better weapon delivery accuracy, but are not directly amenable to the FIREFLY bomb algorithm. The China Lake algorithms compute the TOF and ground range (R_G) by specifying the initial bomb release altitude (h) (above impact point) and the initial vertical (V_{CAY}) and horizontal (V_{CAX}) components of total weapon velocity at bomb release, as illustrated in Figure 17.

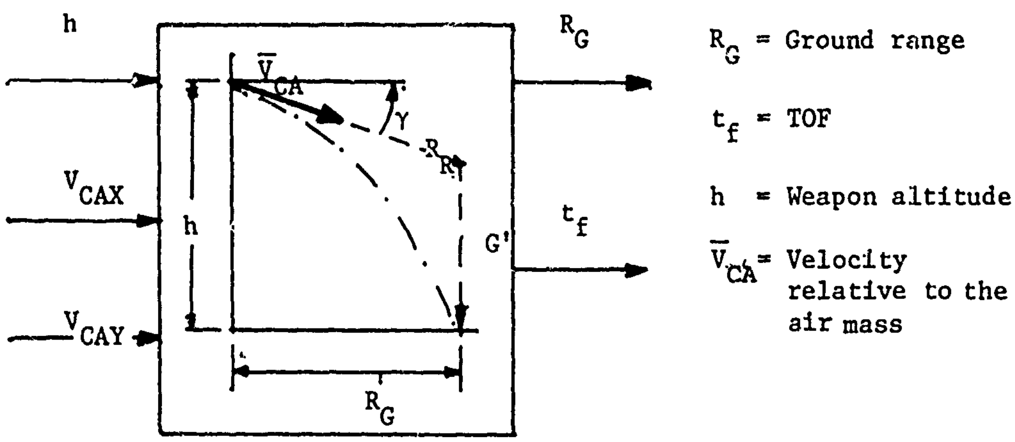


FIGURE 17. CHINA LAKE NUMERICAL INTEGRATION ALGORITHMS

From the geometry in Figure 17 and from the definitions given above the vectors $\overline{R}_R$ and $\overline{G}'$ which define the bomb ballistic trajectory are obtained as follows:

$$\overline{R}_R = \frac{\overline{V}_{CA}}{V_{CA}} \cdot \frac{R_G}{\cos\gamma}$$

$$\overline{G}' = (h + R_G \tan\gamma)\ \overline{Z} \qquad (3\text{-}30)$$

where $\overline{Z}$ is unit vector along the local vertical and γ is the elevation angle of $\overline{V}_{CA}$ relative to the horizontal plane (measured positive counterclockwise).

An iterative solution similar to the one used for the AAG and AGG must be developed if numerical integration is to be used effectively in FIREFLY bombing. This solution can be made to converge on altitude or on slant range depending on which method gives better results.

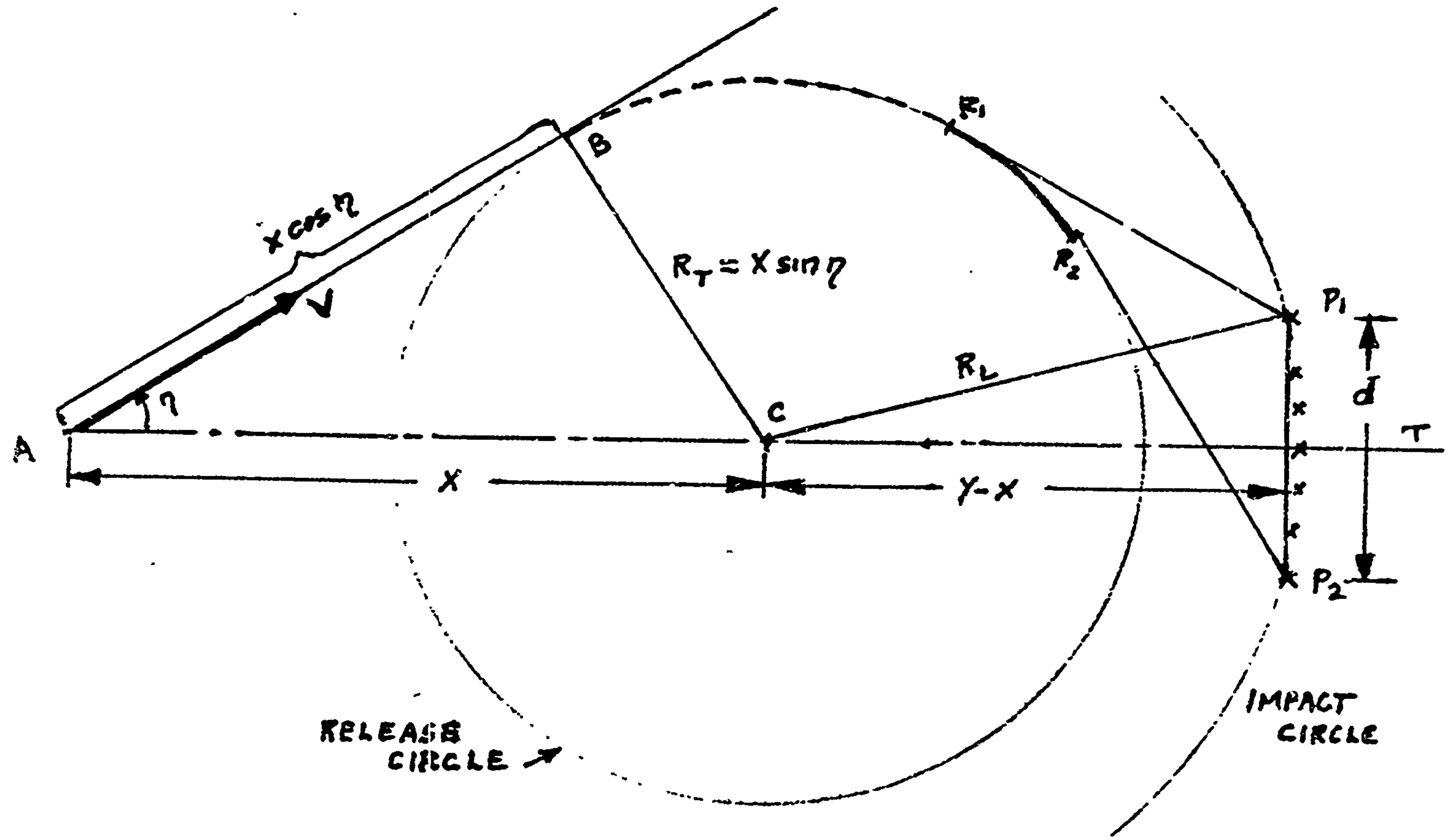
3.2.6 Fire Control Solution for Stick Bombing

The turning rate for FIREFLY/single target bombing is an independent variable which can be chosen conveniently by the pilot. This is, the pilot has the option of initiating the turn immediately or continue at the present course and then make a tighter turn. For stick bombing the turning rate is no longer an independent variable at the pilot's disposal; it must be computed along with the point at which the turn is initiated by the FIREFLY/Stick bombing algorithm.

The geometry for horizontal stick bombing is shown in Figure 18. Since the altitudes and ground ranges associated with the end points of the target are equal, there exists a unique release circle with Center C along the perpendicular bisector AT for which its radius R_T satisfies the relationship in Equation 3-16. The release circle is tangent to the velocity vector at point B, and hence, the flight trajectory consists of a straight line segment $\overline{AB}$ followed by the circular path BR_1R_2. The stick bombing algorithm will be extended to the nonhorizontal turning plane case in the GM design phase.

The weapons will be released between points R_1 and R_2 on the turning circle where the segments $\overline{P_1R_1}$ and $\overline{P_2R_2}$ are tangent to the circle. The distance from any point along the linear flight segment $\overline{AB}$ to the turn initiation point B is referred to as "the distance to go." In addition to this distance, the fire control solution for stick bombing must also compute

- The turning rate, and
- The release points along the circular trajectory.



$\overline{AB}$ - Straight Flight
$\overline{BR_2}$ - Turning Flight

R_1, R_2 - Release Points

FIGURE 18. FIREFLY/STICK BOMBING GEOMETRY FOR HORIZONTAL TURNING PLANE

3.3 STATE ESTIMATION AND FUTURE TARGET POSITION PREDICTION

State estimators compute the required states of ownship, atmosphere, and target using subsystem inputs and reasonable dynamic equations. The target state estimator shall be common for both aerial and ground targets; only the data constraints will be different. The future target position and the kinematic lead vector shall be computed using target state estimates and the weapon TOF.

3.3.1 Ownship State Estimator Requirements

Implementation of the FIREFLY fire control solution requires knowledge of the ownship states with which to reference the target relative motion and obtain the weapon initial conditions. Some ownship states such as angular rates and aircraft orientation are measured directly (or processed) by avionics sensors. To differentiate from these states, only the ownship states which are generated through an estimation, filtering, or data mixing function are considered a part of the ownship state estimation process. These include:

- Ownship accelerations ($\overline{A}_C$)
- Ownship inertial velocity ($\overline{V}_C$)
- Angle-of-attack (α) and sideslip (β)

3.3.1.1 Velocity and Accelcration Estimators

Inertial axes are considered to be fixed rotationally in inertial space with the origin at the center of the earth for computations involving inertial quantities.

Inertial computations incorporating doppler measurements shall consider the effects of earth curvature as a function of altitude if applicable. Ownship velocity and acceleration are computed by one or more of the following sensor outputs.

Stabilized Platform: Sensed accelerations from the INS, ($\overline{A}_S$) can be combined with the gravitational acceleration ($\overline{A}_G$) to provide an estimate of total body acceleration resolved in appropriate coordinates (such as body) as shown below.

$$\hat{A}_{C1} = [BP] \, (\hat{A}_S + \overline{A}_G), \tag{3-31}$$

$[BP]$ - platform to A/C body transformation

Strapdown - Sensed accelerations in body coordinates can be summed with the gravity vector resolved through the HARS, Vertical gyro attitude angles to estimate the total ownship acceleration as in Equation 3-32.

$$\hat{\bar{A}}_{C2} = \hat{\bar{A}}_S + BH \; \bar{\bar{A}}_G \tag{3-32}$$

where [BH] is HARS axes to body axes transformation.

Similarly, ownship inertial velocity can be obtained directly from the INS measurement. If such measurements are not available, ownship inertial velocity can be calculated from doppler radar velocity measurements (or estimates) $\bar{V}_D$ as follows:

$$\hat{\bar{V}}_C = \bar{V}_D + \bar{\Omega} \times \bar{R}_E \tag{3-33}$$

where $\bar{\Omega}$ is Earth's angular rate, $\bar{R}_E$ is Earth's radius and $\bar{\Omega} \times \bar{R}_E$ is calculated in the fire control computer.

An alternate means of computing inertial ownship velocity involves fusing and integrating either or both stabilized platform and strapdown accelerometer outputs, $\bar{A}_{C_1}$, $\bar{A}_{C_2}$ according to

$$\hat{\bar{V}}_C(i) = \hat{\bar{V}}_C(i-1) + \int_{(i-1)\Delta}^{i\Delta} \left[K \, \bar{A}_{C_1}(\tau) + (1-K) \, \bar{A}_{C_2}(\tau) \right] d\tau \tag{3-34}$$

where K is a coefficient ranging from 0 to unity and Δ is the update time.

α, β Estimator

The direction cosines (α^1, β^1) of the air velocity vector $\bar{V}_{CA}$ relative to ownship body coordinates and the associated true Euler angles (α and β) are given by

$$\alpha^1 = V_{CAW}/V_{TAS} \qquad \beta^1 = V_{CAV}/V_{TAS}$$

$$\alpha = \tan^{-1}\left(\frac{V_{CAW}}{V_{CAU}}\right); \qquad \beta = \sin^{-1}\left(\frac{V_{CAV}}{V_{TAS}}\right)^{*} \tag{3-35}$$

*V_{TAS} is the air speed at the IMU or aircraft CG, obtained by applying the proper corrections to measured air speed.

These equations can be used to compute the direction cosines and the true Euler angles directly from the air velocity vector $\overline{V}_{CA}$. An alternate method for estimating the direction cosines α^1 and β^1 is shown in Figure 19. In this figure $\dot{\alpha}^1$ and $\dot{\beta}^1$ are estimated first from acceleration (A_y, A_z) and vane (α^1_m, β^1_m) measurements through a Kalman filter with constant gains K_1, K_2, K_3, and K_4. Integrating the $\dot{\alpha}^1$ and $\dot{\beta}^1$ estimates then yields the desired estimates of the direction cosines $\hat{\alpha}^1$ and $\hat{\beta}^1$.

3.3.2 Atmosphere Estimators

The specific atmospheric parameters that must be measured or estimated include ownship velocity relative to the air mass, air pressure, wind velocity (both horizontal and vertical), air density, and air pressure.

Table 2 is a summary of the assumptions made concerning some of the atmospheric parameters. These assumptions were made for the atmospheric parameter/weapon delivery mode denoted by "No Requirement." In addition, the table also denotes for which parameters there is a requirement to be measured or estimated for each weapon delivery mode. The numbered keys in the boxes refer to the reasons corresponding to the assumptions made or requirements established, and are further discussed in the following section.

TABLE 2

ATMOSPHERIC PARAMETER REQUIREMENTS

Weapon Delivery Mode	Air Velocity	Wind			Air Density
		Horizontal	Vertical	Shear	
A/A Guns	Yes	No Requirement (1)	No Requirement (1)	No Requirement (1), (3)	Yes (4)
A/G Guns	Yes	Yes (2)	Yes (2)	No Requirement (3)	Yes (4)
Bombing	Yes	Yes (2)	Yes (2)	No Requirement (3)	Yes (4)

Reasons for assumptions/requirements:

(1) All wind is ignored for AAG.
(2) Bias due to uncompensated wind is too large to ignore.
(3) No way to measure wind shear.
(4) Required for all air data measurements.

Body Rates $\overline{\omega}$

Wind Velocity Vector $\overline{W}$

Sensed Acceleration $\overline{A}_C$

True Airspeed V_{TAS}

Roll and Pitch Angles ϕ, θ

Vane Measurements α^1_m β^1_m

$$\hat{\dot{\alpha}}^1 = \frac{g \cos\phi \cos\theta + A_Z}{V_{TAS}} + q\left(1 + \frac{W_u}{V_{TAS}}\right) - p\left(\hat{\beta}^1 + \frac{W_v}{V_{TAS}}\right) + K_1\left(\alpha^1_m - \hat{\alpha}^1\right) + K_2\left(\beta^1_m - \hat{\beta}^1\right)$$

$$\hat{\dot{\beta}}^1 = \frac{g \sin\phi \cos\theta + A_Y}{V_{TAS}} + p\left(\hat{\alpha}^1 + \frac{W_w}{V_{TAS}}\right) - r\left(1 + \frac{W_u}{V_{TAS}}\right) + K_3\left(\alpha^1_m - \hat{\alpha}^1\right) + K_4\left(\beta^1_m - \hat{\beta}^1\right)$$

$$\hat{\alpha}^1_i = \int_{t_{i-1}}^{t_i} \hat{\dot{\alpha}}^1 \, dt + \hat{\alpha}^1_{i-1}$$

$$\hat{\beta}^1_i = \int_{t_{i-1}}^{t_i} \hat{\dot{\beta}}^1 \, dt + \hat{\beta}^1_{i-1}$$

K_1, K_2, K_3, K_4 : Kalman Gains

$\hat{\alpha}^1$ $\hat{\beta}^1$

FIGURE 19. AIR VELOCITY VECTOR DIRECTION COSINES ESTIMATOR

For the AAG mode it is reasonable to ignore all wind and wind shear effects. If the air mass at the ownship and target positions (and the space in between) is moving at a uniform rate with respect to the ground (i.e., no wind shear), then for all practical purposes the wind velocity can take on any value at all and it would not matter. What matters is target motion relative to ownship.

For the AGG mode, the average air mass velocity relative to the ground will affect the fire control solution since the aircraft moves relative to the air mass while the target moves relative to the ground. However, if the bullet trajectory computation and future target position prediction are both performed in air mass coordinates, wind velocity will not enter into the computation.

In FIREFLY bombing, the target acquisition and the CCRP computation point differs from the release point. Since the aircraft moves relative to the air mass, the actual release point would move by $\bar{W}t_g$ ($\bar{W}$ = wind velocity, t_g = time to go from acquisition to bomb release) relative to the release point predicted in the air mass. Therefore, wind velocity must be estimated for the bombing mode. Wind will also affect the bomb trajectory through air speed which produces drag.

At first appearance it might seer easonable to ignore all vertical wind since vertical motion of the atmosphere is one to three orders of magnitude smaller than horizontal wind. However, even though the actual vertical wind velocity is small, the contribution of neglecting the vertical wind to the total weapon miss distance is not necessarily small. To illustrate this, Table 3 gives the ballistic range sensitivity to an error in the vertical and horizontal wind velocities for five different release conditions and for a low drag bomb. These sensitivities were generated using Northrop's air-to-ground weapon delivery trajectory simulation program.

TABLE 3. SENSITIVITY OF WEAPON IMPACT POINT TO VERTICAL AND HORIZONTAL WIND

	Release Condition				
Dive Angle (deg.) Altitude (ft.)	0 1000	15 2000	30 3000	45 5000	60 10,000
Vertical Wind Sensitivity(ft/ft/sec)	21.648	11.117	6.745	5.001	4.102
Horizontal Wind Sensitivity(ft/ft/sec)	7.383	6.379	6.112	7.463	11.645

The air velocity vector $\overline{V}_{CA}$ is computed from true air speed measurement V_{TAS} and heading information. Initially, wind direction and magnitude information is received from the meteorology station. Knowing the wind vector and the ground speed from the INS gives the air velocity vector $\overline{V}_{CA}$ which closes the wind triangle. Subsequently, a corrected wind velocity is computed by simply subtracting air velocity vector estimate $\hat{\overline{V}}_{CA}$ from ownship inertial velocity estimate $\hat{\overline{V}}_C$.

$$\overline{W} = \overline{V}_C - \overline{V}_{CA} \qquad (3\text{-}36)$$

3.3.3 Target State Estimator Requirements

The primary function of the target state estimator is to provide accurate estimates of target position, velocity, and acceleration by processing ownship states and designated target position information. Target position information is either supplied by the pilot as a position offset in inertial coordinates or measured through tracking sensors such as EO sensor, radar, and/or laser.

The important ingredients which affect the target state estimator structure are the coordinate frames chosen for the estimation process, the target model, and the observations.

3.3.3.1 Coordinate Frames

Possible coordinates for the estimation process include inertial, ownship body, and polar LOS coordinates. The (slm) LOS coordinates are defined in Section 4.5 where s is along the LOS and ℓ and m are perpendicular to it. Ownship body coordinates can be eliminated based on the argument that the accuracy of the estimates will be affected adversely by body rotation as compared with inertial and polar LOS coordinates.

Both inertial and polar LOS coordinates have been used successfully in target state estimation; the F-16 uses inertial coordinates whereas the F-15 and the FIREFLY II report use of polar LOS coordinates. There are distinct advantages associated with each of these coordinate frames.

Target motion can be best modeled using inertial coordinates (fixed relative to earth or relative to the air mass), while the LOS measurements can be best defined using the polar-LOS coordinates. Therefore, the choice of an appropriate coordinate system for the generalized target state estimator design should be based on a trade-off study to be conducted as part of the design effort. Usually, the choice of coordinate frames is dependent upon the sensor characteristics.

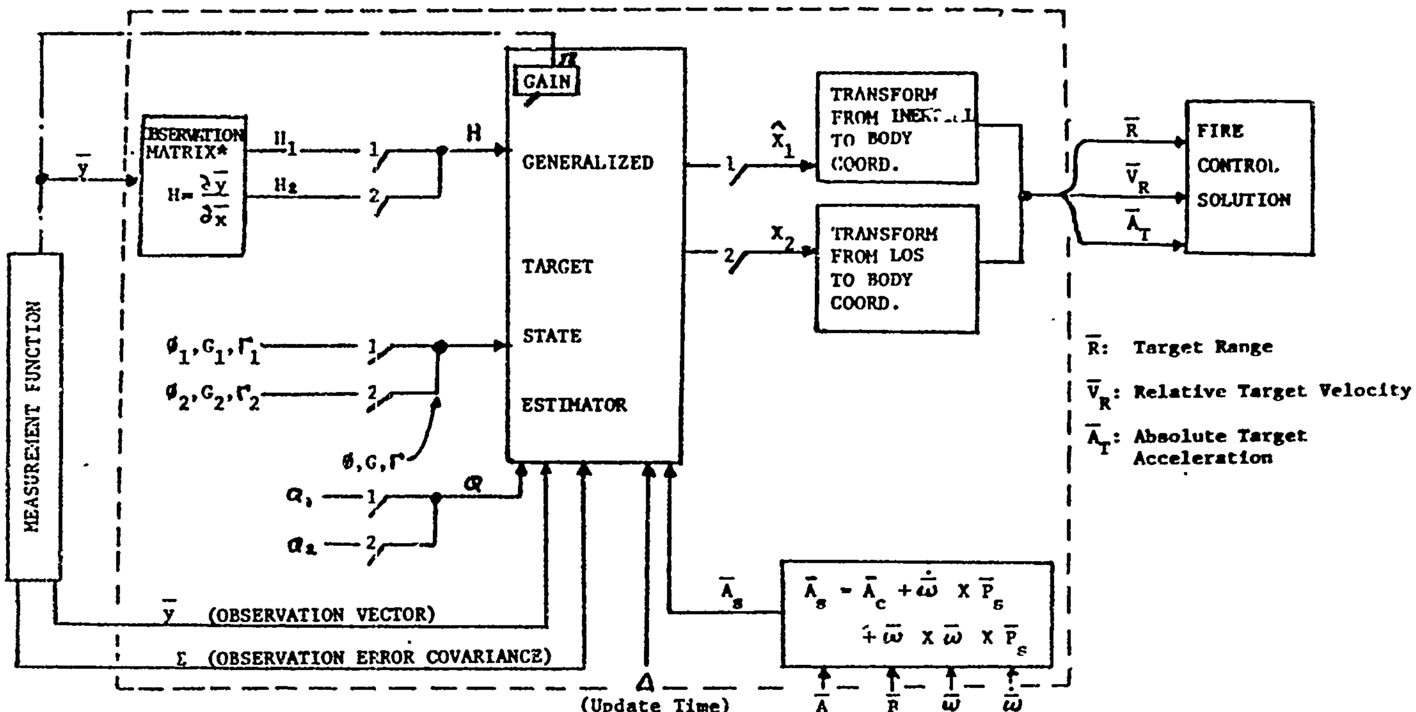
Generalized target state vectors compatible with inertial and polar LOS coordinates are given by:

$$\text{(Inertial)} \quad \overline{X}_1 = \begin{bmatrix} R_X \\ R_y \\ R_z \\ V_{RX} \\ V_{RY} \\ V_{RZ} \\ A_{TX} \\ A_{TY} \\ A_{TZ} \end{bmatrix} \qquad \text{(Polar-LOS)} \quad \overline{X}_2 = \begin{bmatrix} R \\ \dot{R} \\ E_S \\ \omega_{t\ell} \\ T_S \\ \omega_{tm} \\ A_{Ts} \\ A_{T\ell} \\ A_{Tm} \end{bmatrix} \tag{3-37}$$

The components of the state vector $\overline{X}_1$ include target range $\overline{R}$, relative velocity $\overline{V}_R$, and target acceleration $\overline{A}_T$ resolved in (XYZ) inertial coordinates. The components of $\overline{X}_2$ include range (R), range rate (R), elevation (E_S), and azimuth (T_S) angles of the LOS measured relative to ownship body coordinates, angular rates of the LOS perpendicular to the LOS ($\omega_{t\ell}$, ω_{tm}), and the target acceleration resolved in rotating ($s\ell m$) sight coordinates.

Estimates in either inertial or polar LOS coordinates are transformed to ownship body coordinates by using the appropriate transformation matrices. The ($s\ell m$) coordinates are roll-stabilized in which no rolling motion takes place about the s-axis.

To retain flexibility, the generalized state estimator could be designed to operate with both sets of coordinates (inertial and polar -LOS) by closing the appropriate switches shown in Figure 20). The state transition and propagation matrices ϕ, G, and Γ are invariant with the set of sensors used on a specific aircraft and depend only on the coordinate frame selection. The observation matrix H, on the other hand, depends on both the coordinate frame and measurement complement. In this way the



* H is the matrix of partial derivatives of the observation vector $\bar{y}$ relative to the state vector $\bar{X}$.

FIGURE 20. GENERALIZED TARGET STATE ESTIMATOR

impact of sensor availability on estimator design is localized to the selection of an appropriate matrix H, and the estimator is thus modularized. In addition to the observation vector $\overline{Y}$ and the measurement error covariance matrix Σ, the ownship acceleration at the tracking sensor $\overline{A}_S$ must also be supplied as inputs to the target state estimator. The latter is obtained from ownship acceleration at the IMU, A_C, and body rates $\overline{\omega}$ as indicated in Figure 20. Target state estimates are converted from LOS or inertial coordinates to body coordinates where the fire control solution is computed.

3.3.3.2 Target Model

A representative dynamic model which defines the position ($\overline{P}_T$), velocity ($\overline{V}_T$), and acceleration ($\overline{A}_T$) of the target relative to inertial coordinates at any given time is:

$$\frac{d}{dt}\begin{bmatrix}\overline{P}_T\\ \overline{V}_T\\ \overline{A}_T\end{bmatrix} = \begin{bmatrix}0 & I & 0\\ 0 & 0 & I\\ 0 & -\gamma & -\beta\end{bmatrix}\begin{bmatrix}\overline{P}_T\\ \overline{V}_T\\ \overline{A}_T\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \overline{u}\end{bmatrix} \qquad (3\text{-}38)$$

where a random (white) process, $\overline{u}$, is added to the model to introduce randomness into the target motion. β and γ are appropriate 3x3 matrices which define time correlation and interaction effects. This target acceleration model is second-order Gauss-Markov and has sufficient flexibility to allow a wide variety of targets with varying degrees of time correlation to be represented by proper choice of the β and γ matrices. For instance, setting $\beta = 0$ will produce a circular target trajectory for modeling an evasive turn in the AAG mode. Similarly, setting $\gamma = 0$ would allow various ground targets to be represented; $\beta = 0$ corresponds to constant acceleration and $\beta = \infty$ to a rapidly changing, unpredictable acceleration pattern.

3.3.3.3 Observations

Observations will usually involve range to target, LOS direction cosines, and in most cases it will include the angular rates of the LOS. These observations will be obtained from the measurement function discussed in Section 3.5.

3.3.4 Kinematic Lead Vector and Future Target Position

The target dynamic model in Equation (3-38) can be used to predict the target position on TOF in the future. In general, the future target position vector is given by

$$\overline{P}(t_f) = \phi_{11}(t_f) \cdot \overline{P}(0) + \phi_{12}(t_f) \cdot \overline{V}_T(0) + \phi_{13}(t_f)\ \overline{A}_T(0) \tag{3-39}$$

where $\phi_{11}(t_f)$, $\phi_{12}(t_f)$, $\phi_{13}(t_f)$ are 3 x 3 state transition matrices related to the model in (3-38) and $\overline{P}(0)$, $\overline{V}_T(0)$, and $\overline{A}_T(0)$ are current estimates on target position, velocity, and acceleration obtained from the target state estimator. $\overline{V}_T$ is related to the estimated relative target velocity vector $\hat{\overline{V}}_R$ by

$$\overline{V}_T = \hat{\overline{V}}_R + \overline{V}_{CA} + \overline{\omega} \times \overline{P}_S \tag{3-40}$$

The kinematic lead vector, $\overline{KL}$, is defined as the distance traveled by the target during one TOF and is given by

$$\overline{KL} = \overline{P}(t_f) - \overline{P}(0) \tag{3-41}$$

A familiar expression for the kinematic lead vector can be obtained by setting $\beta = \gamma = 0$ in the model in Equation (3-41). The result is:

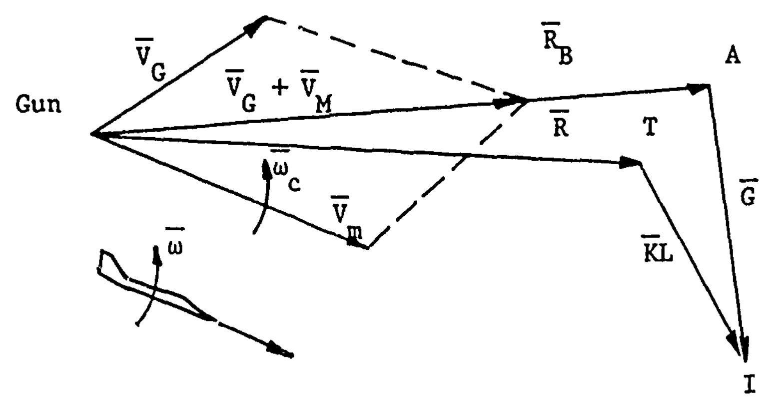
$$\overline{KL} = \overline{V}_T t_f + \frac{1}{2} t_f^{\ 2} \overline{A}_T \tag{3-42}$$

3.4 CONTROL LAW

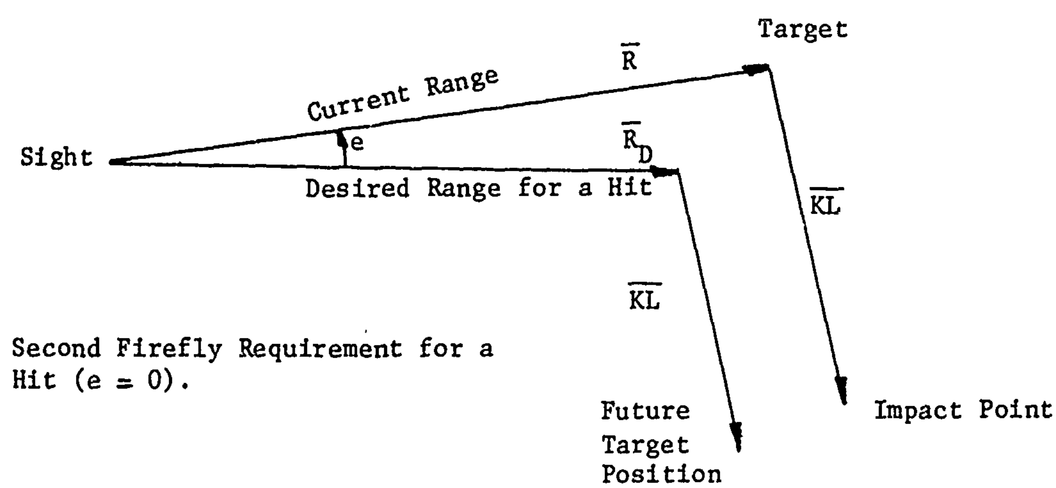
The primary purpose of aircraft control laws is to compute the desired kinematic responses of the aircraft based upon the fire control solutions and to supply controlled inputs to the flight control system (FCS).

3.4.1 Control Laws for AAG and AGG

For AAG and AGG weapon delivery modes the aircraft angular rate command inputs are derived from the fundamental FIREFLY control philosophy which is "to make the aircraft angular velocity vector $\bar{\omega}$ equal to the predicted angular rate associated with the future target position and simultaneously null the angular error between the present range vector $\bar{R}$ and the desired range vector for a hit $\bar{R}_D$." This control philosophy is illustrated in Figure 21 below.



(a) First Firefly Requirement for a Hit ($\bar{\omega}_c = \omega$)



(b) Second Firefly Requirement for a Hit (e = 0).

FIGURE 21. FIREFLY CONTROL REQUIREMENTS FOR A HIT

According to the FIREFLY II control philosophy, pitch and roll rate commands provide coarse adjustment in the aircraft flight path to meet the requirements for a hit, while yaw rate command provides fine tuning in gun aiming to achieve a hit. The angular error between the desired range $\bar{R}_D$ and present range $\bar{R}$ is nulled by turning the aircraft until $\bar{R}_D$ becomes colinear with $\bar{R}$.

The control law is given by

$$
\begin{aligned}
q_c &= q_{CG} + K_v \cdot M \cdot e_v \\
r_c &= r_{CG} + K_w \cdot M \cdot e_w \\
p_c &= K_1 \, (q \cdot r_c - q_c \cdot r) + K_2 \, (q \cdot e_w - r \cdot e_v)
\end{aligned}
\qquad (3\text{-}43)
$$

where K_1, K_2, K_v, K_w are appropriate feedback gains, M is a variable gain function and e_v, e_w are the elevation and azimuth error angles. The control system is shown in Figure 22.

To achieve the desired aircraft response to angular rate commands the flight control system must have a structure similar to that shown in Figure 23. In this figure the proportional plus integral controller in the forward loop insures unity transfer function, in the steady state, between commanded rates and achieved rates.

3.4.2 Additional Control Laws for the AGG Mode

In the AGG mode, the interaction between the longitudinal and lateral aircraft dynamics must be minimized to achieve the desired response fidelity to angular rate commands while performing large evasive maneuvers. Therefore, the control laws for AGG should provide essentially decoupled aircraft responses to pitch rate and yaw rate commands. Decoupled response is also desirable for the AAG mode but not necessary, because for the AAG maneuvers the coupling between the lateral and longitudinal aircraft dynamics is small; hence, omission of decoupling control laws will not cause severe degradation in weapon delivery accuracy.

Additional feedback control laws are required to decouple the lateral and longitudinal aircraft responses for the AGG mode. The decoupling control laws used in the GE FIREFLY II report consist of feedbacks to cancel out the inertial and the aerodynamic coupling terms in the aircraft equations of motion. These control laws essentially provide neutral stability.

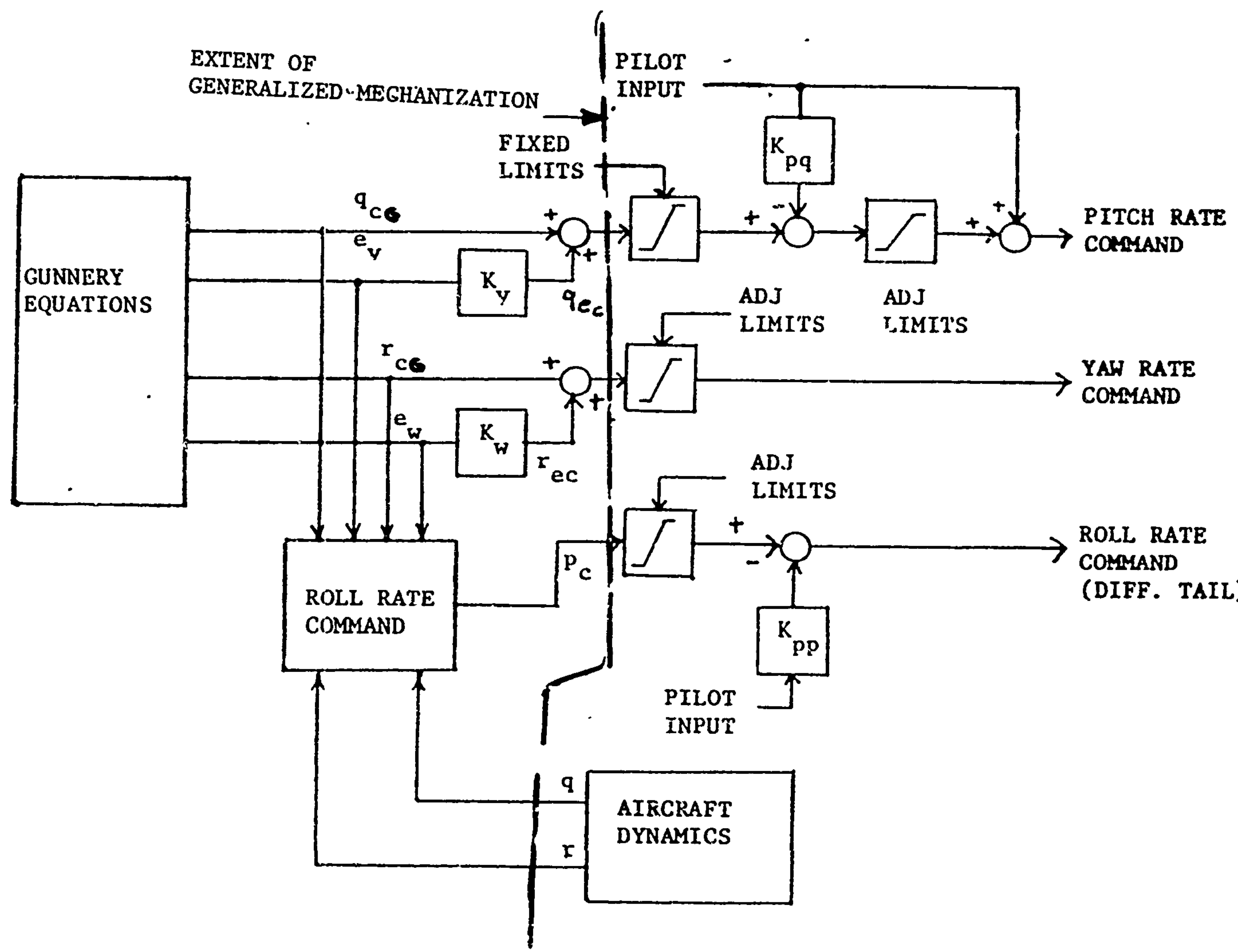
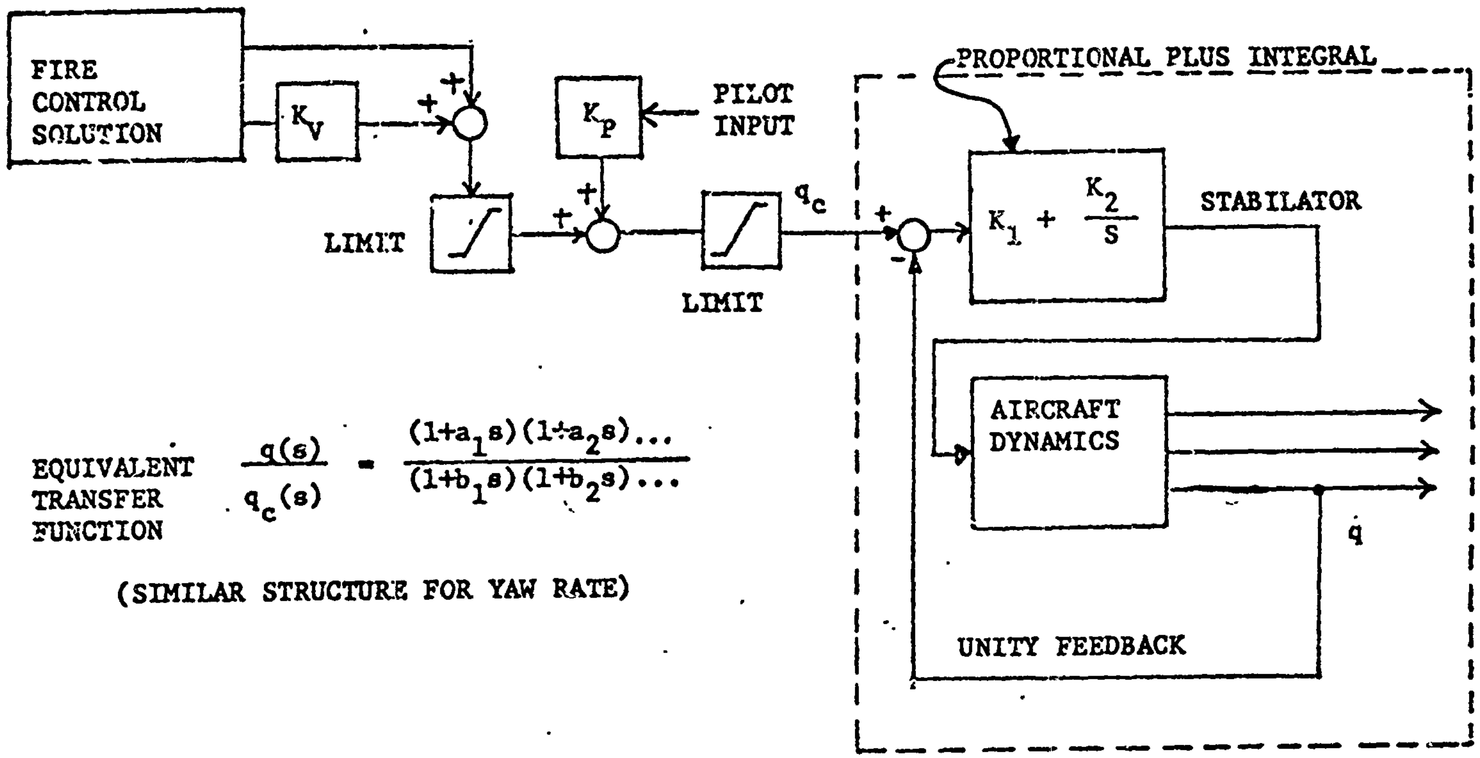


FIGURE 22. AIRCRAFT CONTROL SYSTEM FOR AIR-TO-AIR GUNNERY



EQUIVALENT TRANSFER FUNCTION $\quad \frac{q(s)}{q_c(s)} = \frac{(1+a_1 s)(1+a_2 s)\ldots}{(1+b_1 s)(1+b_2 s)\ldots}$

(SIMILAR STRUCTURE FOR YAW RATE)

FIGURE 23. FLIGHT CONTROL SYSTEM STRUCTURE

The pitching moment and yawing moment equations of the decoupled aircraft have the following form when linearized about the steady flight condition:

$$\dot{q} = M_q \cdot q$$
$$\dot{r} = \frac{Ixz}{Izz}\dot{p} + N_p p + N_r r \qquad (3\text{-}44)$$

where Mq, Np, Nr are stability derivatives and Ixz, Izz are aircraft inertias.

Decoupling control laws similar to those given in the GE FIREFLY II report should be implemented in the flight control system to achieve the desired decoupled aircraft response.

3.4.3 CONTROL LAWS FOR BOMBING

The command signals that steer the aircraft automatically to the release point are derived from the fundamental bombing Equation (3-17). The objective of the control law is to adjust the orientation of the angular rate vector $\bar{\omega}$, by controlling aircraft roll rate until it becomes colinear with the vector $\bar{C}_P$.

$$\bar{C}_P = \bar{S}_V \times \bar{r}_P \qquad (3\text{-}45)$$

As shown in the GE FIREFLY II report, the roll rate command is given by

$$P_C = -K_R \epsilon_u / |\bar{C}_P|^2 \qquad (3\text{-}46)$$

where ϵ_u is the component of the error vector $\bar{\epsilon}$

$$\bar{\epsilon} = \left(\frac{R_P^2 - R_R^2}{2\, V_{CA}}\right) \bar{C}_P \times \bar{\omega} \qquad (3\text{-}47)$$

in u-body axis and K_R an appropriately chosen feedback gain.

In addition to generating the steering commands for conventional aircraft the generalized mechanization for bombing must also

- Provide steering commands for the A-10, and
- Be compatible for stick bombing.

In the FIREFLY approach the pilot sets the magnitude of $\bar{\omega}$ by controlling turn rate, the direction of $\bar{\omega}$ is made equal to the direction of $\bar{C}_P$ by controlling roll rate and the TOF is computed from the magnitude equality of the vectors on both sides of Equation (3-17). The TOF determines the release point relative to target position.

Two alternate approaches for using the pitch control axis of the A-10, instead of the roll control axis, for steering the aircraft to the release point were developed in Appendix C.

The first method derives the control law from the magnitude equality and the second method derives the control law from the direction equality. Other methods were suggested by the AFAL. One of them involves using the v and w components of the vectors instead of the magnitude and direction to solve for the TOF and the steering commands.

These control laws must be evaluated in the control law design phase and combined with the FIREFLY bombing algorithm to design an integrated generalized mechanization for bombing.

3.5 MEASUREMENT FUNCTION AND AVIONICS SUBSYSTEM

The measurement function receives as its input the outputs of all possible avionic subsystems under consideration by the AFFA. Associated with each avionic sensor output is a requirement to specify all errors of quantities measured by that sensor (such as means, variances, and power spectra) to the extent that these are known from avionic sensor test data. The measurement function must also contain generalized "mixing" logic such that simple mixing of data (data fusion) from sensor outputs can be selected and supplied as inputs to the state estimator function via a suitable choice of the measurement specialization parameter, Msp. The specification and design of Msp will enable any meaningful combination of sensor quantities to be selected for a given avionic configuration. Figure 24 shows the avionics subsystem/measurement function/generalized mechanization interface. The measurement function supplies the observation vector $\bar{y}$, and the collection of statistical information Σ such as observation error covariance, correlation time, measurement biases, etc. to the remainder of the GM. In some applications information must also be supplied directly from the measurement function to the state estimator in order to turn the Kalman gains on or off in accordance with the availability of measurements. The measurement function will also have to make any coordinate transformations necessary on sensor data.

Table 4 shows the avionics subsystem/measurement function (MF) interface. Under the avionics subsystems (left column in the table) all applicable avionics sensors are listed. The outputs of these sensors become inputs to the MF which generates the generic inputs to the GM (outputs of the MF). The measurement specialization parameter, which must be specified by the user of the GM, determines what sensor combination is available and thus determines the specific function to be performed by the MF.

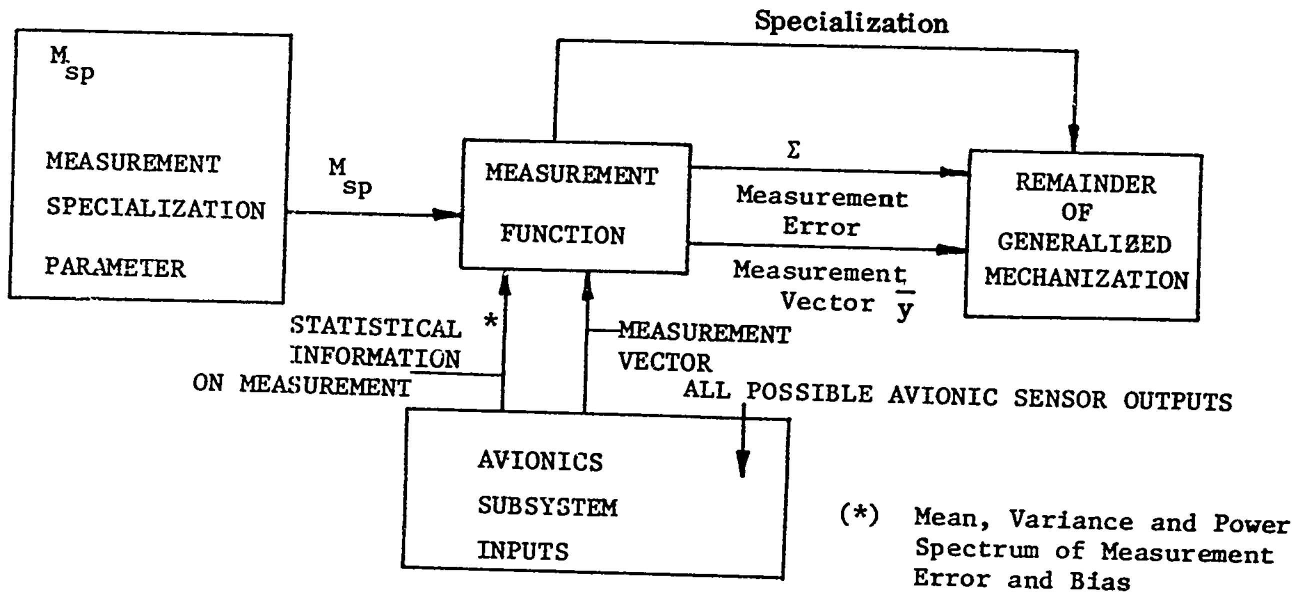


FIGURE 24. AVIONICS SUBSYSTEM – GENERALIZED MECHANIZATION INTERFACE

TABLE 4. AVIONICS SUBSYSTEM/MEASUREMENT FUNCTION INTERFACE

AVIONICS SUBSYSTEM (Measurement Function Input)	INPUT TO REMAINDER OF GM (Measurement Function Output)
INS	Ownship Inertial Position
• Velocity (V_N, V_E, V_V)	
• Acceleration (A_N,A_E,A_V)	Ownship Inertial Velocity ($\overline{V}_C$)
• Gimbal Angles (Hdg, θ, $\emptyset$)	
• Lat - Lon. (Φ,Λ)	
• Ownship Inertial Position	Ownship Inertial Acceleration ($\overline{A}_S$) (Sensed)
STRAPDOWN IMU	
• Acceleration (A_u, A_v, A_w)	
• Euler Angles (ψ, θ, $\emptyset$)	Ownship Transformation From Inertial to Body [E]
• Body Rates (p, q, r)	Ownship Angular Rates $\overline{\omega}$
AIR DATA SENSOR	
• True Air Speed (V_{TAS})	True Airspeed (V_{TAS})
• Angle of attack (α)	Angle of Attack (α)
• Sideslip Angle (β)	Angle of Sideslip (β) (if measurement is available)
• Relative Pressure (p/p_o)	
• Relative Air Density (ρ/ρ_o)	Relative Air Density (ρ/ρ_0)
• Temperature (T)	
• Pressure Altitude (h)	
• Mach Number	
RADAR (DOPPLER)	
• Velocity-ground speed (V_D)	

TABLE 4. AVIONICS SUBSYSTEM/MEASUREMENT FUNCTION INTERFACE (CONTINUED)

AVIONICS SUBSYSTEM (Measurement Function Input)	INPUT TO REMAINDER OF GM (Measurement Function Output)
ELECTRO-OPTICAL TRACKER	TARGET RELATIVE STATE VECTOR
• Range	• Range (R)
• Gimbal Angles (T_S, E_S)	• Range Rate ($\dot{R}$)
• Tracker Rates (ω_t, ω_c, ω_d)	
• Gimbal Angle Rates($\dot{T}_S$, $\dot{E}_S$)	
RADAR TRACKER	
• Range (R)	
• Gimbal Angles (T_S, E_S)	• Tracker Angular Rates
• LOS Rates (ω_t, ω_c, ω_d)	• Tracker axis direction cosines
• Gimbal Angle Rates ($\dot{T}_S$, $\dot{E}_S$)	
• Range Rate ($\dot{R}$)	
INS	GRAVITY VECTOR
• Gimbal Angles (θ, Ø, Hdg)	• Transformation Platform to Body
HARS	
• Euler Angles (θ, Ø, Hdg)	• Transformation Vertical Gyro Platform to aircraft body.
MUZZLE VELOCITY SENSOR	GUN MUZZLE VELOCITY ($\overline{V}_M$)
• Muzzle Velocity (V_M)	
HELMET SIGHT	HELMET ORIENTATION
• Helmet Angles (T_h, E_h) or Direction Cosines	Direction Cosines or Helmet to Body Transformation
RADAR ALTIMETER	ALTITUDE (h)
• Altitude above surface.	

4.0 GENERALIZED MECHANIZATION REQUIREMENTS

The primary objective of the Advanced FIREFLY Assessment (AFFA) Program is to provide a single software tool that is versatile enough to simulate specific mechanizations and to evaluate the designs of these Integrated Fire Flight Control (IFFC) system mechanizations for a wide variety of aircraft and avionic subsystems. In this regard, design considerations for the GM must include the interdependency of different requirements of the functions that make up the GM portion of the AFFA.

The gross structure of the GM has been identified in Section 2 and expanded in detail in Section 3 of the GMRR. This section identifies specific requirements within each of the four major functions comprising the GM:

1. Fire Control Solution Function
2. State Estimator Function
3. Control Laws Function
4. Measurement (Avionic Subsystem Inputs) Function

In addition, requirements for coordinate frames and a definition of symbology to be used for the GM design are included in this section.

In general, the GM requirements can be divided into three categories:

1. Functional Requirements
2. Accuracy Requirements
3. Hardware (or equipment) requirements

The requirements category mostly dealt with in this GMRR are the functional requirements. The accuracy requirements will be addressed in subsequent tasks of the AFFA program. However, a top level requirement is identified herein, that can be stated as follows:

> "The generalized mechanization and each of its constituent functions shall meet the accuracy requirements imposed upon it, such that the overall specified weapon delivery accuracy is met."

4.1 FIRE CONTROL FUNCTION REQUIREMENTS

The generalized mechanization (GM) for Firefly shall compute the fire control solution for three basic weapon delivery modes: AAG, AGG and bombing. The GM shall be based upon but not limited to Firefly II algorithms and shall encompass other than Firefly weapon delivery modes listed on Table 5 on the following page.

TABLE 5
WEAPON DELIVERY MODES

Air-to-Air Gunnery (AAG)	. 20 mm gun director submode . LCOS submodes for non-tracked targets . Transition from non-track to track modes
Air-to-Ground Gunnery (AGG)	. All CCRP types of weapon delivery for projectiles and rockets
Bombing	. Direct and indirect sub modes . CCRP/INS direct submode . Angle rate bombing system . Indirect (or blind) coordinate bombing . Offset bombing . Stick bombing

Moreover, the GM of the fire control solution algorithms shall satisfy the following additional requirements:

1. Fire control algorithms shall be expressed in terms of the vectors used in the fire control geometry. This approach allows for modifications to be made in any of the vector expressions without affecting the overall fire control structure, and hence is consistent with the GM requirements.

2. Versatility shall be provided for using either closed-form expressions or numerical integration techniques for computing the weapon ballistic trajectory.

3. The weapon TOF computation algorithm shall converge rapidly to produce a fire control solution in real time consistent with airborne computer computational constraints.

4. The effect of sight parallax, gun parallax, bomb parallax, and bomb rack delay shall be included in the derivation of fire control equations.

5. Fire control equations shall be developed for the large angle case without making the small angle approximation made in the FIREFLY II report.

6. The Generalized Mechanization of ballistic algorithms shall be capable of controlling the delivery of the weapons listed below. The fire control solution shall have the capability of calculating the impact point and time of flight of all these weapons.

   20mm Guns
   30mm Guns
   Rockets
   Low Drag General Purpose Bombs
   Two-stage/Cluster Weapons

7. Numerical integration algorithms shall, to the maximum extent possible, be identical for the AAG, AGG and bombing modes. Further, the integration algorithms shall be highly adaptable to different types of unguided ordnance.

8. The fire control solution shall compute the following variables:

<u>Variables Common To All Weapon Delivery Modes</u>

- Future target position
- Predicted weapon impact point
- Predicted miss distance
- Weapon TOF from release to impact
- Ballistic trajectory component vectors along the total velocity vector and along gravity.

<u>Additional Variables for the AAG and AGG Modes</u>

- Gunline direction cosines for a hit
- Desired range for a hit
- Gun lead angle
- Aircraft angular rate commands.

<u>Additional Variables for Bombing</u>

- Weapon release point
- Time to go before release
- Steering commands
- Range vector $\bar{R}_p$ from current attacker position to a point directly above the desired weapon impact point on the turning plane.

Additional Variables for Stick Bombing

- Distance to go along a linear flight path before initiating the turn and the associated turning rate.
- Range vector $\bar{R}_p$ defined above for each of the endpoints of a linear target.

4.2 STATE ESTIMATION FUNCTION REQUIREMENTS

The state estimators shall consist of ownship state estimator, atmospheric estimator, and target state estimator. In addition to these estimators the state estimation function shall predict the future target position and the kinematic lead vector by using the target state estimates.

4.2.1 Ownship State Estimator Requirements

The ownship state estimator final requirements must necessarily await an error budget derived from detailed error analysis of the postulated available measurements. Since ownship rotational quantities such as angular rates and orientation are usually measured accurately by sensors, there may be no need to estimate them.

The ownship state estimator for the GM design shall be based on the following assumption which becomes a requirement on the OFP.

> "The avionic subsystem will include an INS or a strapdown system which measures, at a minimum, the ownship inertial acceleration."

From a qualitative and structural point of view the following GM estimator requirements can be defined.

4.2.1.1 Inertial Acceleration and Velocity Estimator

The inertial acceleration and velocity estimator shall perform the following functions:

1. Estimate the ownship inertial acceleration and velocity from measurements provided by gimbaled and/or strapdown IMU's.
2. Be capable of computing ownship inertial acceleration and/or velocity by fusing any linear combination of acceleration or acceleration integrals respectively.

3. Compute inertial velocity from doppler radar estimated velocity and earth surface velocity. (See Section 3.3.1.1)

4. Provide any linear combination of velocity estimates for improving accuracy or testing degraded modes.

All transformations required to generate a useful ownship motion output in any appropriate coordinate system shall be defined and provided.

4.2.1.2 Angle of Attack and Sideslip Estimators

The α, β estimator shall provide accurate estimates of air velocity vector direction cosines or estimates of the angle of attack and sideslip angle, from pertinent measured or computed quantities. These quantities may include the following:

1. Sensed body accelerations and velocities from the IMU.
2. Aircraft body rates.
3. α and/or β vane measurements, if any.

The α, β estimators shall be capable of producing accurate estimates for large aircraft maneuvers (large α close to stall and large sideslips). The estimates shall not depend critically on the aircraft stability and control derivatives.

4.2.2 Atmosphere Estimator Requirements

The atmospheric estimator shall have the capability to:

1. Estimate the ownship relative air velocity,

2. Obtain smooth estimates of air density, atmospheric pressure and baro altitude above mean sea level,

3. Compute the wind velocity relative to inertial coordinates using the estimated ownship inertial velocities and the estimated air velocities.

4.2.3 Target State Estimator Requirements

Essential to any gunfire control system is the ability to predice the future trajectory of the target during the TOF of the projectile. Future target position is predicted from current target state estimates obtained by processing LOS and ownership measurements through an Extended Kalman filter.

In addition to providing accurate estimation of the target states, the generalized target state estimator must satisfy the following requirements:

1. Interface with various avionic sensors including multiple sensors.
2. Be compatible with various weapon delivery modes, such as AAG, AGG and bombing.
3. Be compatible with alternate (inertial and LOS) coordinate frames for estimating target states.
4. Have a modular design with interchangeable computational blocks; such as alternate target acceleration subfunction and alternate Kalman gain subfunction.
5. Be based on a representative target acceleration model of moderate complexity which includes acceleration rate dependence on target acceleration as well as on target velocity.
6. Have a means of correcting the Kalman gains in the event modeling errors tend to produce filter divergence.
7. Account for state dependent measurement noise sources in the filter design.
8. Compensate for correlated measurement noise and measurement bias, whenever possible, in the estimator design.
9. Any augmented state variables which represent measurement bias, drift rates, misalignment, etc., shall be fed back to, or accounted for in the estimator design to improve the state estimation performance.
10. The target state estimator shall be as invariant as possible for various tactical aircraft with differing avionics and shall provide maximum commonality for specialized mechanizations.

In order to design a practical and implementable target state estimator which satisfies all of the requirements listed above, it is necessary to make the following simplifying assumptions.

1. All avionic sensor outputs are synchronized and updated at the same rate through an "avionic interface" before they are supplied to the generalized estimator. Additional errors and correlation introduced by measurement averaging will be accounted for as part of the measurement function design.

2. Sensor output mixing (or data fusion) is performed in the "measurement function" external to the state estimator. Data compression considerations and pertinent coordinate transformation will be included in the measurement function design.

3. Signals required to drive the target tracker will be generated externally to the state estimator.

4.2.4 Future Target Position Prediction and Kinematic Lead

Target position one TOF in the future shall be computed using target state estimates, the computed TOF, and representative target acceleration models.

4.3 CONTROL LAW REQUIREMENTS

The primary purpose of an aircraft control law is to supply controlled inputs to the flight control system (FCS). In conformity with the GE type of control laws the inputs to the FCS shall be in the form of pitch, yaw, and roll rate steering command inputs and they shall be compatible with various weapon delivery modes (AAG, AGG, and bombing) and for differing conventional and CCV-type aircraft. Alternate weapon delivery mode and aircraft compatibility is provided in the FCS interface (or coupler) which conditions the steering command inputs before they are applied to the FCS.

The objectives of the control law are twofold:

- To generate steering command inputs for various weapon delivery modes, and
- To adapt the steering command inputs, through a coupler, to a specific aircraft.

The coupler shall be designed based on the following requirements:

1. The combination of coupler and FCS shall provide wideband and well damped aircraft responses to angular rate steering command inputs as the aircraft characteristics for a given flight condition would permit. This requirement may be met by compensating the FCS for a specific aircraft to achieve the desired responses.

2. The coupler shall be designed to meet the gain and phase margin stability requirements of the augmented aircraft specified by MIL-F-94901.

3. Proportional plus integral controller shall be used in the forward loop to provide unity transfer function in the steady state as shown in Figure 23.

4. Authority sharing between the pilot and the automatic Firefly steering system shall be built into the coupler design with pilot override provision.

5. The automatic steering command signals and aircraft load factor shall be limited for a specific aircraft to ensure structural integrity and to prevent the aircraft from getting into an uncontrollable flight regime.

6. Control parameters of the coupler (gains and time constants) shall not depend directly on aircraft stability derivatives and flight control parameters, but on aircraft design limits such as load factor and roll rate.

7. Wherever possible the coupler shall be designed in such a way as to minimize the sensitivity of aircraft responses to aircraft dynamic parameter variations in the flight envelope.

8. The FCS shall have gust rejection capability. Attitude sensitivity to gust is desirable in gunnery whereas load factor insensitivity to gust is desirable for bombing.

9. Full utilization of the direct lift and direct side force capability of the CCV-type aircraft shall be made in the coupler design to improve the offensive and survivability capability of the aircraft.

10. Decoupling control laws shall be incorporated, especially for the AAG mode as indicated in Section 3.4.2 to eliminate or minimize interaction between longitudinal and lateral aircraft responses.

11. These additional control laws shall not produce undesirable response characteristics although some compromise in stability may be inevitable. In many instances the use of decoupling control laws and/or gust alleviation control systems would lead to neutral stability.

In the 11 July 1978 correspondence to the AFAL/RWT it was stated that:

> "Design efforts for the Control Augmentation System (CAS) coupler are deleted as suggested. Northrop will utilize the F-15/16 CAS designs defined by the Firefly II studies and assume that CAS designs for the A-10, ATF, and CCV aircraft will be provided by the Air Force. Northrop will work with the Air Force to establish the simplified flight control-aerodynamic transfer function representatives based upon the specified CAS designs.
>
> If a necessity develops during the course of the study to improve CAS characteristics to optimize the SAM avoidance concept, the Air Force will be informed and additional design efforts may be established at a future time."

Therefore, the coupler design for a variety of aircraft is outside the scope of the present AFFA Program. It is assumed that the user of the generalized Firefly mechanization will supply the appropriate coupler in conjunction with the specific aircraft model to be simulated.

Requirements which relate to the generation of steering commands which apply directly to the GM design are listed below:

1. The steering control laws shall be updated at such a rate as to prevent aliasing and interaction with the structural modes but not faster than necessary to conserve computing time.
2. The control law shall include the proper compensation such as rate mixing to compensate for the aircraft response lag, the computation time in the fire control computer, and the update time on the MUX bus. Compensation shall not affect closed-loop stability and shall preferably be done outside the FCS feedback loops.
3. Bombing control laws shall include provision for stick bombing and shall include the flexibility of using either the roll or the pitch axis control system of a generic aircraft to allow the Firefly control laws to be implemented on the A-10 with minimum modifications.

The control law requirements listed above apply to fixed guns and fixed stores but not to trainable guns. For fixed guns, fuselage aiming for AAG is achieved by rotating the aircraft in pitch and yaw relative to earth until the total projectile velocity is pointed to the desired aimpoint which takes into account weapon ballistics and gravity drop.

4.4 MEASUREMENT FUNCTION AND AVIONICS SUBSYSTEM REQUIREMENTS

The distinction between the avionics subsystem and the measurement function is clearly defined in Section 3.5 of this GMRR. The avionic subsystem shall include all applicable sensors and shall supply the measurements to the measurement function (MF). The latter shall generate all generic parameters, such as range, ownship velocity and orientation, etc., required for the fire control solution. The inputs and outputs of the MF shall include, but not be limited to the measurement quantities listed in Table 4. Selection of appropriate combinations of sensors or measurement shall be provided by the measurement specialization parameter "Msp". Specification of Msp shall provide the required generic inputs to the GM from a specific combination of sensors.

The requirements for the MF are listed below:

1. The MF shall provide measurement mixing and data fusion as required to generate a single output quantity for each generic variable such as range, aircraft velocity, etc.
2. All outputs of the MF shall be synchronized and updated at the same rate.
3. Additional measurement errors introduced as a result of measurement averaging (due to correlation) for data synchronization shall be accounted for in the measurement error covariance computation.
4. Each sensor shall be identified as having or not having any internal filtering, smoothing, or state estimation. For each sensor output quantity or set of quantities which have been filtered, there shall be specified a measurement error covariance matrix, bias error, and a filtering lag time.
5. State dependent noise and correlated measurement noise characteristics of each sensor shall be identified and this information shall be supplied to the state estimators for inclusion in the design process.
6. Data compression shall be accounted for and pertinent coordinate transformation shall be provided in the MF.

4.5 COORDINATE FRAMES REQUIREMENTS

The coordinate systems used for the fire control solution shall be orthogonal and right-handed and shall consist of the following:

N, E, D -	Inertial or earth-fixed coordinates; N - north, E - east and D - down.
u, v, w -	Attacker body coordinates, u - forward along the roll axis, v - out to right wing along the pitch axis, and w - down along the yaw axis.
u_w, v_w, w_w -	Attacker wind coordinates, u_w - along attacker velocity relative to the air mass. v_w - to the right and w_w - down.
s, ℓ, m -	Sight coordinates, s - along the target line-of-sight, ℓ - out to the right and m - down.
t, c, d, -	Tracker coordinates, t - along the tracker axis, c - to the right along the tracker elevation axis and d - completing the orthogonal system.
s_h, ℓ_h, m_h -	Helmet sight coordinates, s_h - along the target sight, ℓ_h out to the right and m_h - down.

Any vector can be transformed from one set of coordinates to another set of coordinates by using the following transformation matrices.

Inertial to Attacker Body Transformation [E]

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = [E] \begin{bmatrix} N \\ E \\ D \end{bmatrix}$$

Wind to Attacker Body Transformation [W]

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = [W] \begin{bmatrix} u_w \\ v_w \\ w_w \end{bmatrix}$$

Attacker Body to Sight Transformation [T]

$$\begin{bmatrix} s \\ \ell \\ w \end{bmatrix} = [T] \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

Attacker Body to Tracker Transformation [F]

$$\begin{bmatrix} t \\ c \\ d \end{bmatrix} = [F] \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

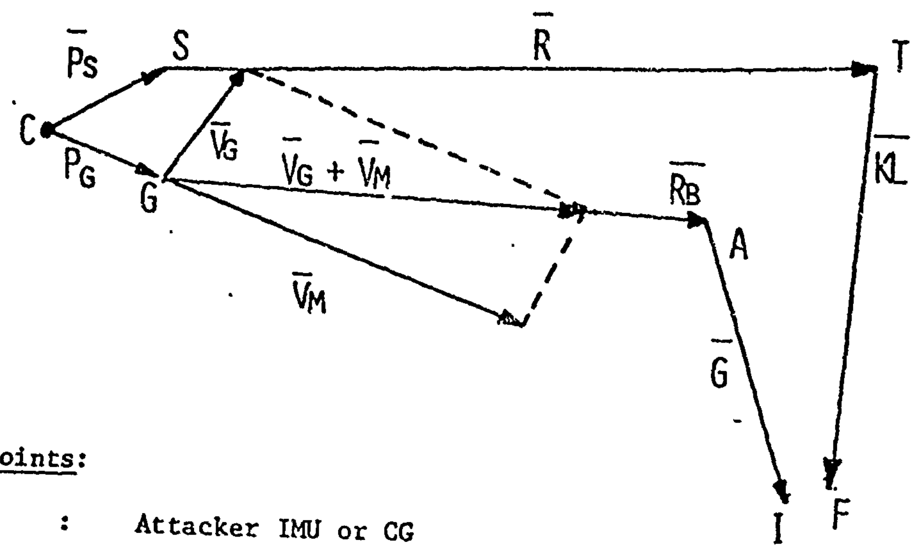
Attacker Body to Helmet Sight Transformation [H]

$$\begin{bmatrix} s_h \\ \ell_h \\ m_h \end{bmatrix} = [H] \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The generalized mechanization shall use the most efficient means of constructing the transformation matrices [E], [W], [T], [F], [H] and others, if any. Quaternions, Euler angles, direction cosines shall be among the candidate systems to be considered in the design. The selection between these alternate means of computing the transformation matrices should be based upon physically measurable quantities available on a specific aircraft.

4.6 NOMENCLATURE REQUIREMENTS

1. The GM shall be designed using the nomenclature defined in this section. The coordinate transformations and coordinate components shall be as defined in Section 4.5
2. The fire control mode point and vector definitions shall be those described in Figure 25 for AAG and AGG, Figure 26 for the turning plane geometry for bombing, Figure 27 for the vector diagram at turn initiation for bombing, and Figure 28 for the vector diagram at the release point for bombing.
3. Vectors shall be represented by symbols with an overbar.
4. Estimated parameters shall be represented by symbols with hat.
5. Time derivatives will be represented by overdots, one for first and two for second.



Points:

C : Attacker IMU or CG

S : Attacker Sight

G : Attacker Gun

T : Present target position

F : Future target position

A : Aim point

I : Weapon impact point

Vectors

$\overline{P}_S$: Parallax, attacker IMU to sight

$\overline{P}_G$: Parallax, attacker IMU to gun

$\overline{R}$: Present range to target

$\overline{KL}$: Kinematic lead vector

$\overline{G}$: Gravity drop

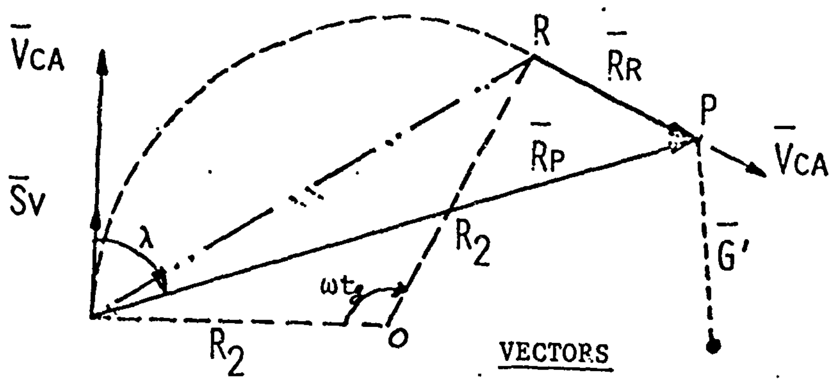
$\overline{R}_B$: Weapon travel along total velocity vector $\overline{V}_M + \overline{V}_G$

$\overline{V}_G$: Attacker velocity at gun station

$\overline{V}_M$: Muzzle velocity along gunline

FIGURE 25. VECTORS ASSOCIATED WITH AAG AND AGG FIRE CONTROL MODE

CIRCULAR FLIGHT PATH



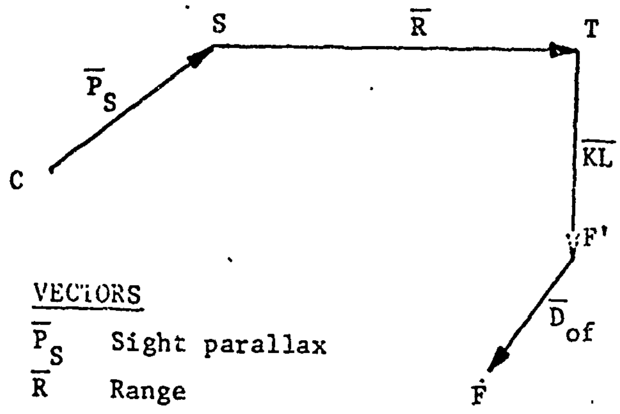
POINTS

O	Origin of turning circle
C	IMU location (or aircraft CG) at turn initiation
R	Bomb release point
P	Point on turning plane directly above weapon impact point
I	Weapon impact point

VECTORS

$\overline{V}_{CA}$	Ownship velocity relative to air
$\overline{S}_V$	Unit vector along $\overline{V}_{CA}$
$\overline{R}_P$	Vector from point C to point P
$\overline{R}_R$	Weapon travel along $\overline{V}_{CA}$ from release to point P.
$\overline{G}'$	Vertical drop of weapon
R_2.	Radius of turning circle
λ	Angle between $\overline{V}_{CA}$ and $\overline{R}_P$

FIGURE 26. - TURNING PLANE GEOMETRY FOR BOMBING



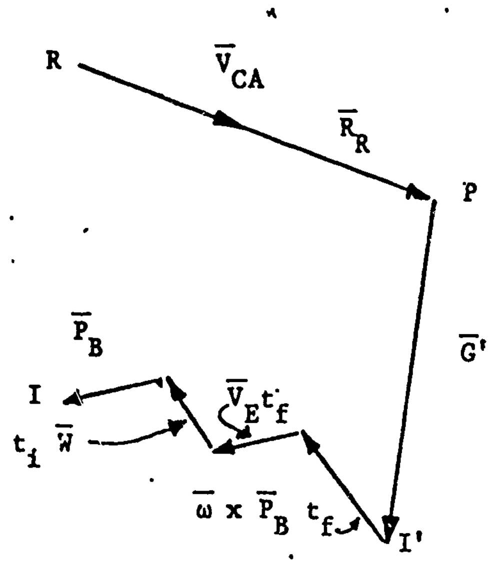
POINTS

C	IMU location at turn initiation
S	Target tracking sensor
T	Present target position
F'	Future target position
F	Desired weapon impact point

VECTORS

$\overline{P}_S$	Sight parallax
$\overline{R}$	Range
$\overline{KL}$	Kinematic lead
$\overline{D}_{of}$	Target position offset

FIGURE 27. VECTOR DIAGRAM AT TURN INITIATION



<u>VECTORS</u>

$\overline{W}$ Wind velocity relative to inertial coordinates

$\overline{P}_B$ Bomb parallax

$\overline{V}_B$ Ownship velocity at bomb location

$\overline{V}_E$ Bomb ejection velocity relative to body

$\overline{V}_{CA}$, $\overline{R}_R$, $\overline{G}'$ Defined above.

FIGURE 28. VECTOR DIAGRAM FOR BOMB RELEASE POINT COMPUTATION

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APPENDIX A

FIREFLY II CONCEPTS

1.0 CONCEPT DESCRIPTION

FIREFLY II offers a way to couple the aircraft's flight and fire control systems in order to introduce refinements in weapon delivery through the use of partial automatic control of these tasks. In the case of A/A combat, the integration of flight and fire control systems results in improvements in gunnery accuracy as well as in reductions of pilot work load. For A/G missions, the effects of FIREFLY II are a decrease in the vulnerability to anti-aircraft artillery (AAA) and surface-to-air missile (SAM) threats and an increase in the weapon delivery accuracy. These are consequences of the fact that FIREFLY offers an alternative to the traditional technique of rolling out to a wings level attitude before releasing the weapons. In contrast to this, FIREFLY II allows bombing during execution of a turn in a plane which is not restricted to be horizontal. For AGG, FIREFLY facilitates the execution of an evasive maneuver while simultaneously maintaining the gun line on the target. The possibility of evasive aircraft maneuvers while engaged in A/G combat increases the problem for the AAA and SAM by making the flight path less predictable and the maneuver requirements more difficult.

The integration of fire and flight control systems is achieved in FIREFLY II by the generation of command signals which are used to steer the aircraft. The system has been designed with the capability to offer several levels of pilot participation in the control tasks, varying from pilot-aided semi-automatic control to manual control.

For automatic control of AAG, the basic philosophy in the FIREFLY II design is to induce colinearity of the angular velocities of the aircraft and of the LOS to the target's future position and, at the same time, to zero out the angular errors of the gun.

In AGG the basic approach in FIREFLY II is to augment the sideslip angle during the firing interval rather than to coordinate the aircraft, as is done traditionally. The presence of a sideslip angle does not cause significant aiming errors if its value is estimated properly. It does lead to a reduction in the time available for an AAA to achieve an effective burst, as well as an increase in the miss distance for AAA fire directed against the aircraft.

The FIREFLY II bombing system offers the capability to deliver weapons in high-G turns initiated from any dive or roll angle, and does not call for precise control of aircraft lift. The approach consists of determining the release conditions as a function of the turn rate magnitude. The range at which the bomb should be released is displayed to the pilot, whose task is to continue to turn at a constant rate until the release range is reached.

In the following paragraphs, various topics relating to the General Electric FIREFLY II concept will be discussed. These topics include the familiarization with the FIREFLY II concepts, methods for determining the weapon delivery accuracy when FIREFLY II is implemented, and, finally, work performed in the analysis of the FIREFLY II control laws using the Terminal Aerial Weapon Delivery Simulation (TAWDS) program.

Although fire control algorithms were developed in the General Electric FIREFLY II report, considerable work was done by Northrop during the familiarization phase to extract the information and tie the various parts of the algorithm together into an integrated fire control system.

2.0 FIREFLY II FAMILIARIZATION

The block diagram of the FIREFLY II system for the AAG and ACG weapon delivery modes is shown in Figure A-1. Symbols used in this Figure and in the equations that will follow are defined in Table A-1.

As shown in Figure A-1, the angular rate of the antenna, the measured target range, and the off-boresight angle of the LOS to the garget, as well as ownship velocity and acceleration are inputs to the target state estimator. The estimates of the target variables are then used to generate the target relative state vector, which is required as input to the gunnery equations. These equations compute the desired angular rates that should be imparted to the gun and also supply estimates of the gun-aiming errors. The outputs of the gunnery equations serve to generate the pitch, yaw, and roll rate commands which, in turn, affect the aircraft's position, velocity, and acceleration and effectively close the loop.

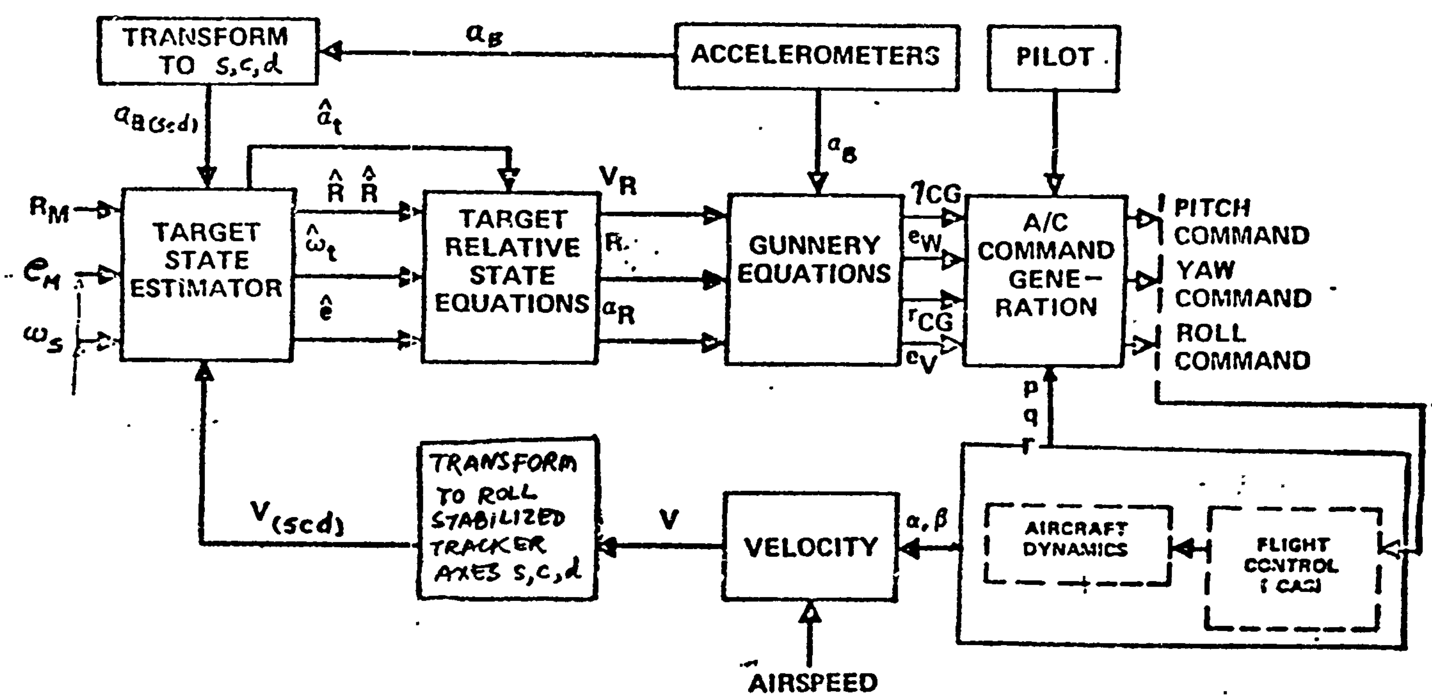


FIGURE A-1. FIREFLY II FIRE CONTROL SYSTEM FOR AAG AND AGG

TABLE A-1. DEFINITION OF TERMS FOR FIREFLY II CONTROL SYSTEM

q_{CG}, r_{CG}	=	Gun pitch and yaw rate commands
e_M	=	Off-boresight angle of target LOS
V	=	Aircraft velocity
V_T	=	Target velocity relative inertial coordinates
V_R	=	Relative target velocity
R	=	Target range vector
$\dot{R}$	=	Range rate
R_M	=	Measured target range
a_t	=	Target acceleration
a_B	=	Aircraft body acceleration
a_R	=	Relative target acceleration
a	=	Ownship acceleration
ω_s	=	Angular rate of tracker axis
ω_t	=	Angular rate of target LOS
ω_{slm}	=	Angular velocity of tracker coordinates
$e_{\bar{v}}, e_{\bar{w}}$	=	Aiming error components
p, q, r	=	Roll, pitch, yaw rate of aircraft
η	=	Process noise in target model
D_f	=	Future target range
V_a, V_M	=	Attacker's airspeed and muzzle velocity
T_f	=	Time of flight
α, β	=	Angle of attack, sideslip

The preceding description omits the fact that the coordinate systems associated with each functional block are not the same and that transformations from one system to the other are required throughout the loop. These coordinate systems include inertial coordinates, aircraft body coordinates, (uvw), LOS coordinates (slm) and roll stabilized tracker coordinates (scd).

A2.1 Target State Equations

The following differential equations define the target state estimator:

$$
\begin{aligned}
\dot{\bar{e}} &= \bar{\omega}_t - \bar{\omega}_s \\
\dot{\bar{\omega}}_t &= \frac{1}{R}\left[\frac{\bar{R}}{R} \times (\bar{a}_t - \bar{a}) - 2\dot{R}\,\bar{\omega}_t\right] \\
\dot{\bar{R}}_{slm} &= \bar{V}_t - \bar{V} - \bar{\omega}_{slm} \times \bar{R} \\
\dot{\bar{a}}_{t_{scd}} &= -\beta\bar{a}_{t_{scd}} + \bar{\eta} \\
\dot{\bar{V}}_{t_{slm}} &= \bar{a}_t - \bar{\omega}_{slm} \times \bar{V}_t
\end{aligned}
\qquad \text{(A-1)}
$$

A2.2 Target Relative State Equations

The target relative velocity along the antenna line of sight is given by:

$$V_{RS} = \dot{R}$$

The relative velocity normal to the line of sight is computed from

$$\bar{\omega}_t = \frac{\bar{R} \times (\bar{V}_t - \bar{V})}{R^2} \qquad \text{(A-2)}$$

The target relative acceleration is

$$\bar{a}_R = \bar{a}_t - \bar{a}. \qquad \text{(A-3)}$$

A2.3 Gunnery Equations

The gunnery equations include calculation of the bullet TOF, T_f and of the gun rate and error signals which serve to generate the aircraft commands.

a. Time of Flight Computation

Target position T_f seconds in the future is predicted by using the following equation.

$$\overline{D}_f = \overline{R} + \overline{V}_T T_f + \frac{1}{2} \overline{a}_t T_f^2 \tag{A-4}$$

The relationship between T_f and future range D_f is expressed by

$$T_f = \frac{D_f}{V_a + V_M - C_B D_f} \quad ; \quad C_B = \left(\frac{\rho}{\rho_o}\right) K_D \ |V_a + V_M| \tag{A-5}$$

where V_a is the attacker's airspeed, V_M is the average muzzle velocity and C_B is the ballistic coefficient which is proportional to the square root of total projectile velocity ($V_a + V_M$). Manipulation of the above two equations leads to a cubic polynomial in T_f, which is solved by iteration.

b. Gun Rate Commands

The FIREFLY control laws require that the turn rate commands nominally drive the gun at the angular rate of the future position of the target.

In vector form, the gun angular rate commands ω_{CG} are given by

$$\overline{\omega}_{CG} = \frac{1}{D_1} \left[\overline{U} \times (\overline{V}_R + T_f \overline{a}_R)(1 + \dot{T}_f) + T_1 \ (\overline{U} \times \overline{a}) + T_f \dot{T}_f (\overline{U} \times \overline{a}_b) \right]$$

$$- \overline{U} \times (\overline{\omega} \times \Delta\overline{U}) \tag{A-6}$$

where

$$D_1 = \frac{T_f V_M}{1 + C_B T_f} \quad , \quad T_1 = \frac{C_B T_f^2}{1 + C_B T_f}$$

and where $\overline{U}$ is a unit vector along the aircraft u-body axis, $\overline{\omega}$ is the aircraft angular velocity, $\Delta\overline{U}$ is the vector differences between $\overline{U}$ and a unit vector along the gunline, and $\dot{T}_f$ is the time rate of change of T_f given by:

$$\dot{T}_f = \frac{\dot{R}\ (1 + T_f\ C_B)}{2\ T_f\ (C_B\ V_{TS} + 0.5\ a_{TS}) + C_B\ R + \dot{R} - V_M - V_M\ \sin^2(\lambda/2)} \qquad \text{(A-7)}$$

c. Required Range for a Hit

The angular gun errors are defined as the angular separation between the LOS to the target and the LOS required for a hit, R_R. The latter, expressed in vector form, is given by

$$\overline{R}_R = \frac{T_f}{1 + C_B T_f}\ \overline{V}_M - \frac{C_B T_f^{\,2}}{1 + C_B T_f}\ \overline{V}_a - T_f \overline{V}_R - \frac{1}{2}\ T_f^{\,2}\ (\overline{a}_b + \overline{a}_R) \qquad \text{(A-8)}$$

where all symbols have been identified in the preceeding paragraphs.

If both $\overline{R}_R$ and the actual range to the target $\overline{R}$ are expressed in the attacker's body axes (u, v, w), the components about the v and w axes of the gun pointing errors become:

$$e_{LV} = \frac{R_{Rw} - R_w}{R}$$

$$e_{LW} = \frac{R_{Rv} - R_v}{R} \qquad \text{(A-9)}$$

d. Generation of Aircraft Commands

Figure A-2 summarizes the main features of the AAG control system.

Now q_{CG} and r_{CG} are the body axes components of $\overline{\omega}_{CG}$, the angular rate of predicted future target position, and (p, q, r) represent the ownship body rates.

The rate commands are generated as a linear weighted sum of the angular velocity of the future position of the target and the present gun aiming errors.

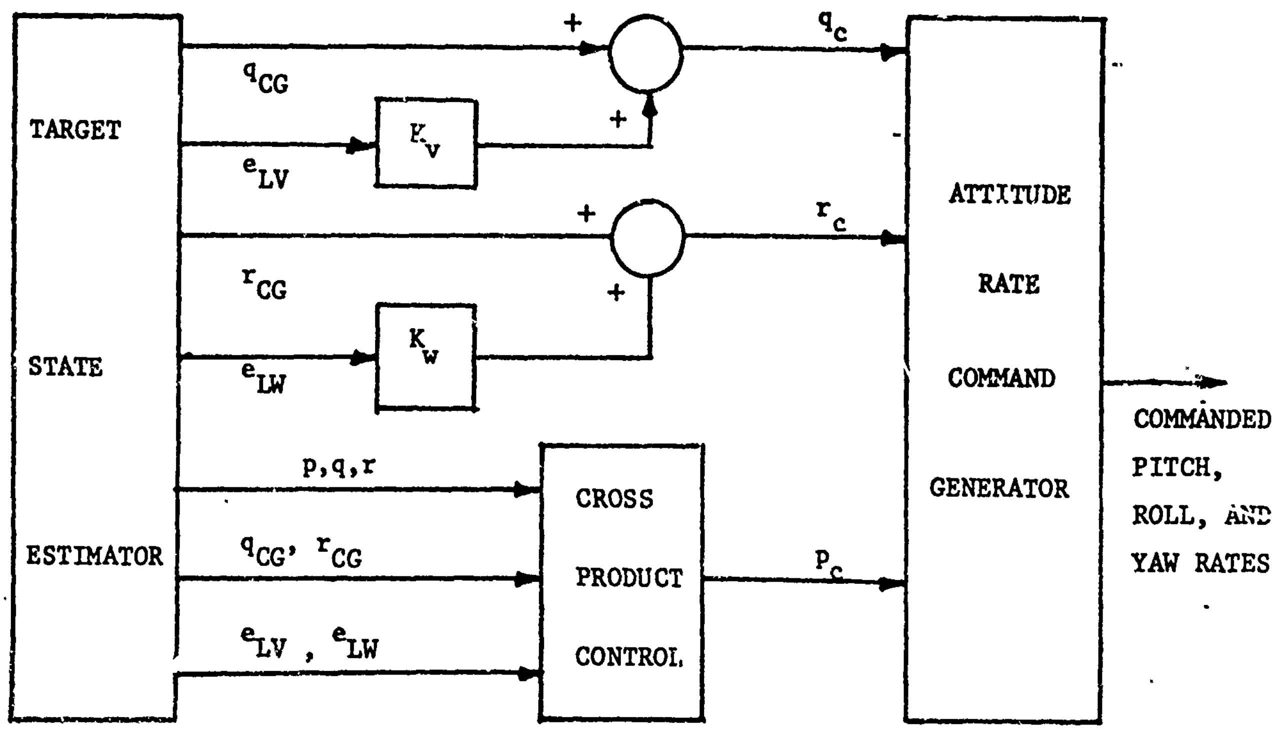


FIGURE A-2. AIR-TO-AIR GUNNERY CONTROL SYSTEM

3.0 FIREFLY II TAWDS ANALYSIS

Following the initial familiarization with the FIREFLY II control laws, a simulation of their performance was carried out using a six-degree of freedom nonlinear program named Terminal Aerial Weapon Delivery Simulation (TAWDS). (Reference 6). Both A/A and A/G versions of this program exist, but only the A/A FIREFLY II laws were implemented.

An abbreviated block diagram of TAWDS (A/A) is shown in Figure A-3. As indicated, the program simulates an attack on a target by a weapon system consisting of a pilot and a fighter aircraft with its flight control, sight, and weapon delivery systems. The TAWDS program propagates stationary and dynamic source errors into statistical impact error distributions. Stationary source errors considered arise from the flight profile and system mechanization errors. Dynamic source errors are those due to atmospheric disturbances, weapon release forces, and pilot steering tasks. The performance output data for the TAWDS (A/A) program are time history responses for the attacker and target aircraft responses, plots of specified attack aircraft weapon delivery time history responses, stationary source error printouts, ensemble pass statistics printouts for the tracking error responses, and ensemble pass statistics printouts for the bullet impact error.

The approach taken to incorporate the FIREFLY II control laws into TAWDS was to replace the blocks inside the dashed rectangle in Figure A-3 by equivalent ones, as shown in Figure A-4. By this choice, the aircraft was flown exclusively using the commands generated by FIREFLY II rather than be a mixture of pilot and automatic control commands. Substitution of the aircraft's control system dynamics and airframe response by simplified transfer functions were dictated by the fact that the aircraft modeled in TAWDS is an F-4 and that the detailed aerodynamic data required by TAWDS was not available for the F-15 aircraft. For this reason, transfer functions relating the rate commands to the actual body rates were derived using data from the F-15's FIREFLY II results. An additional simplification was introduced by assuming that the velocity, angle of attach and sideslip angle of the attacker were constant during the encounter. As was the case in the FIREFLY II report, a director gunsight was considered.

The results of the simulation showed that the elevation and traverse tracking errors stayed below 0.5 degrees in an encounter between an F-15 and a maneuvering target represented by an F-4.

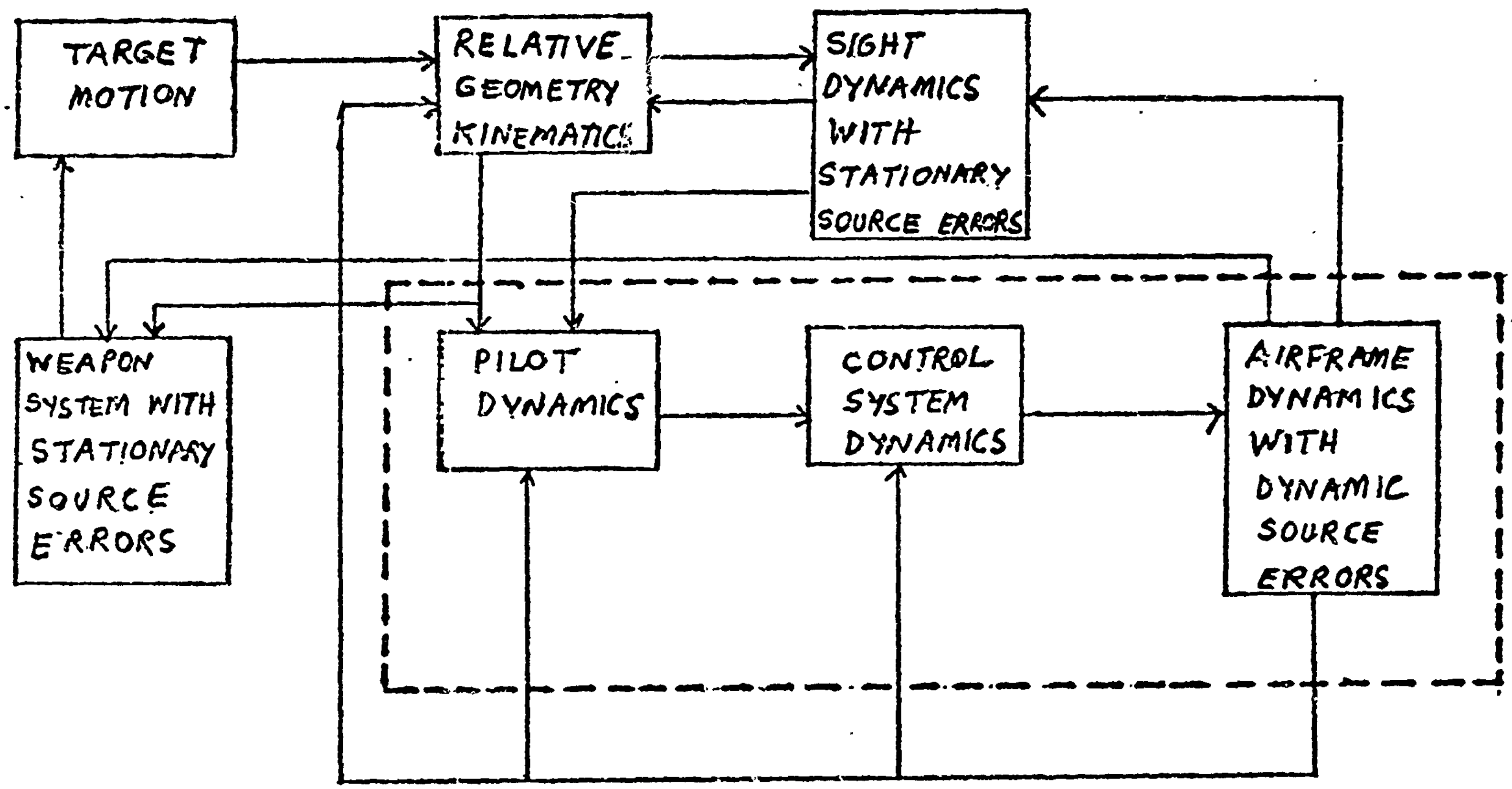


FIGURE A-3. TAWDS (A/A) BLOCK DIAGRAM

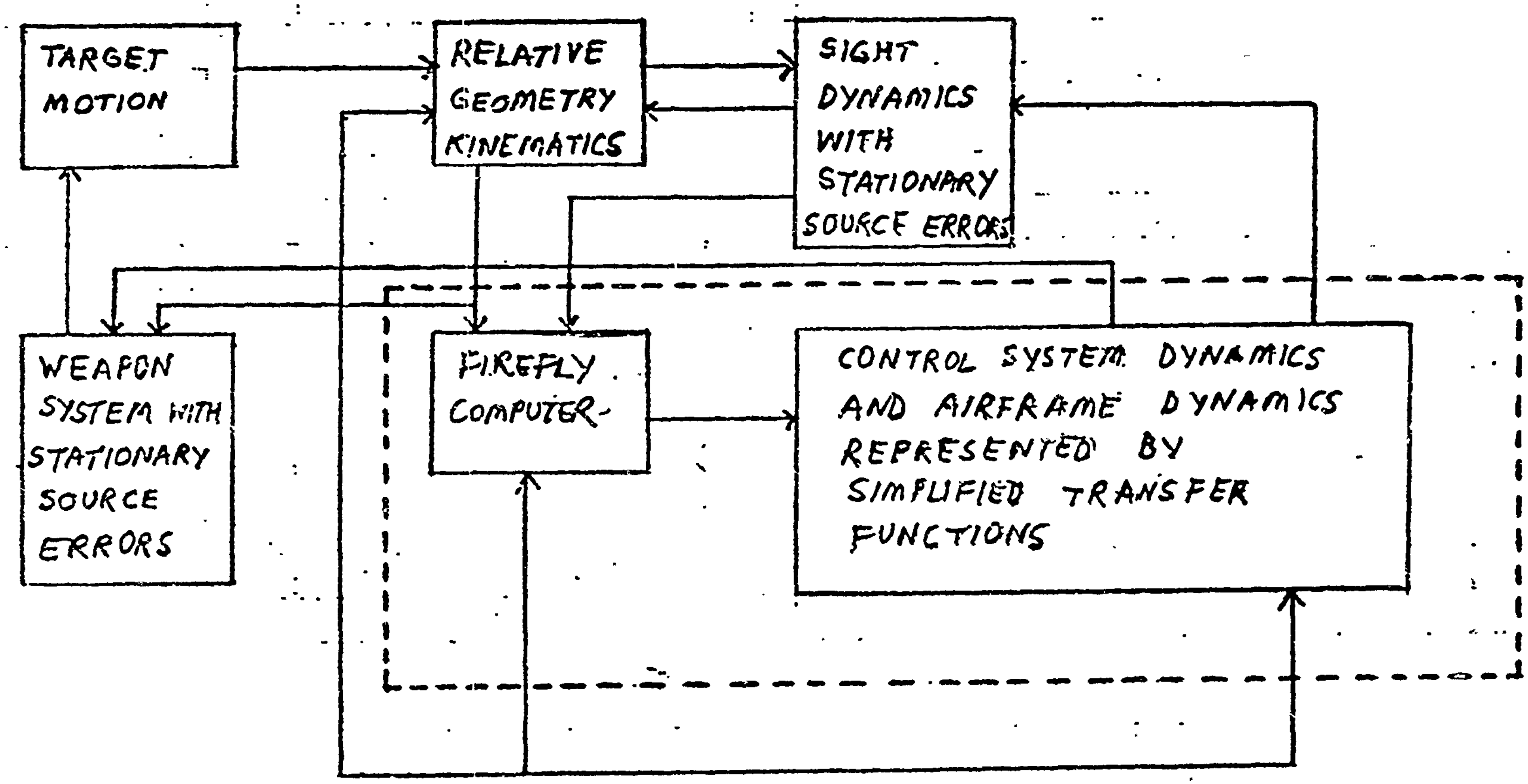


FIGURE A-4. FIREFLY-TAWDS (A/A) INTERFACE

APPENDIX B

DATA FUSION TECHNIQUES

Techniques for fusing multiple sensor outputs are summarized and the relationship between these techniques and the Advanced FIREFLY Assessment program are indicated in Table B-1.

TABLE B-1

RELATIONSHIP OF DATA FUSION TECHNIQUES TO AFFA PROGRAM

Data Fusing Techniques	Relationship to AFFA Program
• Selection of one sensor out of multiple sensor	Integral Part of FIREFLY II GM
• Optimally mixed sensors based on - Noise Covariance - Noise spectrum - Time response • Semi-adaptive measurement mixing • Parallel Filtering • Filtered Sensor Output	New Concepts
• Fully adaptive Kalman filtering	Outside the scope of AFFA Program

The simplest means of dealing with multiple sensors which measure the same variable is to pick the more accurate of the two for the particular operating condition. This scheme was considered as part of Advanced FIREFLY GM. On the other hand, a fully adaptive Kalman filter estimator was considered to be outside the scope of the AFFA program. The remaining data fusion techniques listed in Table B-1 were classified as "new concepts" and were investigated during the requirements analysis phase of the AFFA Program.

Optimally mixing the sensor outputs improves the accuracy of the measurement (or the estimate), with minimum addition of the fire-flight control system. For instance, these techniques may provide between 80 percent and 90 percent of the accuracy achieved through a fully adaptive Kalman filter, at a fraction of the complexity. Moreover, the fully adaptive Kalman filter usually has a slower response time than an ordinary Kalman filter to prevent instability caused by interaction between the filtering loop and the loop which adaptively varies the Kalman gains in response to the measurement error covariance. The flow filter time response is an undesirable feature of the fully adaptive Kalman filter.

Combining multiple sensor outputs provides back up protection in the event of sensor failure and sensor jamming in addition to reducing the measurement error. Since the radar is easily jammable, a jamming detector can be used to detect the presence of jamming signals and switch to another sensor automatically. Despite the advantages of data fusion there are limited applications wherein the available sensor outputs can be combined optimally. Typical examples include mixing the angle measurements from EO sensor and monopulse radar and combining the range measurements from radar and the laser.

Among the techniques listed above in Table B-1 those techniques which can be easily included in the GM involve adding multiple sensor outputs with fixed gains. Other techniques are sensor-dependent and therefore, they do not conform with the GM concepts. These more complicated techniques could be studied in follow-on work as they relate to specific applications and specific combinations of sensor.

Optimal Mixing Based on Measurement Error Covariance

Figure B-1 shows a technique for mixing the multiple sensor outputs based on apriori knowledge of measurement noise covariances. The fixed gains, C_1 and C_2 in this figure are given by

$$C_1 = \frac{R_2}{R_1 + R_2} \quad ; \quad C_2 = \frac{R_1}{R_1 + R_2} \qquad \text{(B-1)}$$

where

$$R_1 = \mathrm{Cov}(X_1) \quad ; \quad R_2 = \mathrm{Cov}(X_2)$$

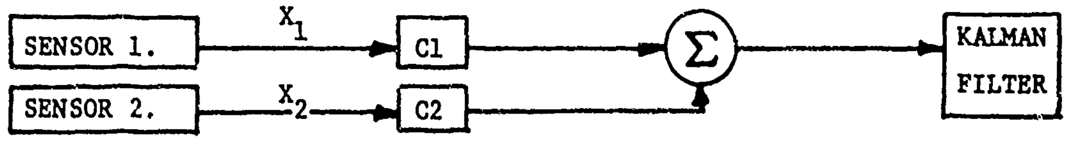


FIGURE B-1. OPTIMAL MIXING BASED ON MEASUREMENT ERROR COVARIANCE

The error covariance of the optimally mixed output, X,

$$\mathrm{Cov}(X) = \frac{R_1 R_2}{R_1 + R_2} \tag{B-2}$$

is smaller than the covariance of either sensor output. Hence, by mixing the sensor outputs as shown in Figure B-1 the measurement error covariance will be reduced and the accuracy of the measurement will be improved. Maximum improvement is obtained when $R_1 = R_2$ in which case the covariance of X is one half the covariance of either sensor output as shown by the knee in the curve in Figure B-2. As the ratio R_1/R_2 deviates from unity, the improvement decreases to the point where sensor output mixing no longer becomes practical. For instance, to decrease the covariance to 80 percent of the error covariance of the more accurate sensor, R_1/R_2 must lie between 0.25 and 4. Outside this interval mixing the sensor outputs becomes impractical.

If the measurement error covariances R_1 and R_2 are not known precisely, setting the gain C_1 to other than $R_2/(R_1 + R_2)$, will result in suboptimal mixing in which the combined measurement is still more accurate than either measurement, as long as C_1 lies in the interval:

$$1 > C_1 > \frac{R_2 - R_1}{R_2 + R_1} \tag{B-3}$$

for $R_1 < R_2$. Outside this interval, the mixed output, X, will be less accurate than the more accurate sensor output X_1. This, of course, defeats the purpose of data fusion. Therefore, ballpark values for the measurement error covariances must be known before attempting data fusion.

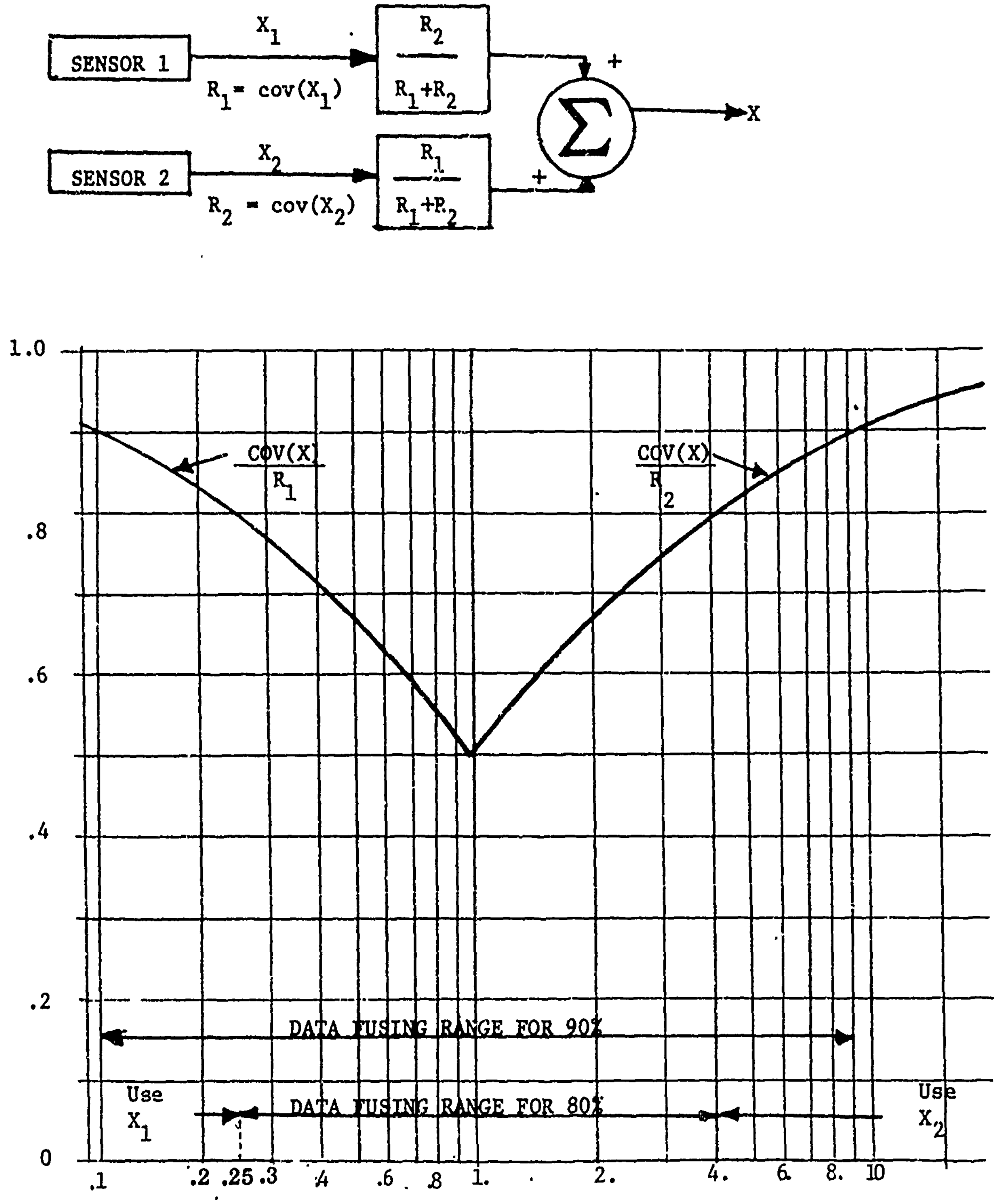


FIGURE B-2. PRACTICAL BOUNDS FOR MIXING SENSOR OUTPUTS

APPENDIX C

A-10 CONTROL LAW MODIFICATION

1. INTRODUCTION

FIREFLY II algorithms generate a roll control law for automatically steering the aircraft toward the release point. The roll axis control system on the A-10 is not accessible for inserting external commands without major modifications to the flight control system. Therefore, the feasibility of using the pitch axis control system of the A-10 (which is accessible) instead of the roll axis control system, for automatically steering the aircraft toward the release point is investigated herein as one of the "new concepts" in the AFFA program.

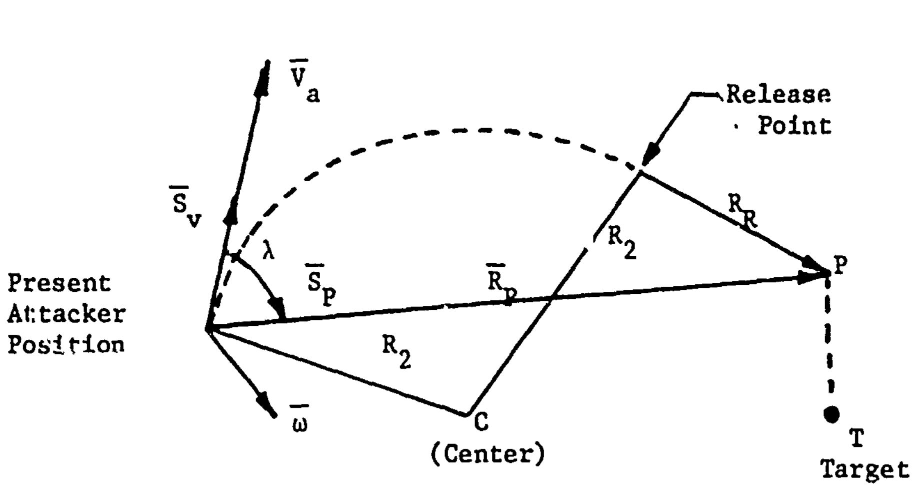
Incorporation of a modified control law for the A-10 into the FIREFLY II bombing algorithm will simply involve switching the appropriate control axis and using the the associated computational method.

2. FIREFLY II BOMBING CONCEPT

The FIREFLY II bombing system provides for a maneuvering approach to bomb release from a non-wings level attitude. There exists a fundamental relationship among the encounter parameters to execute the proper maneuver for accurate bomb release. This relationship takes the form of equating the magnitude and direction of two vectors associated with the bomb release geometry.

The basic guidance equations for bombing are obtained from Figure C-1 which shows the geometry on a turning plane. From this geometry one has the following fundamental relationship that must exist among the encounter parameters if the attacker is to execute a constant rate maneuver from present position to the release point at a specific TOF:

$$\sin \lambda = \frac{R_p^2 - R_R^2}{2 V_a R_p} \omega \tag{C-1}$$



P	=	Point directly above target
C	=	Center of circular bombing trajectory
R_2	=	Radius of circle
$\overline{V}$	=	Attacker velocity vector relative to air mass
$\overline{\omega}$	=	Angular rate vector
$\overline{S}_V$	=	Unit vector along $\overline{V}$
$\overline{S}_P$	=	Unit vector along $\overline{R}_P$

FIGURE C-1. TURNING PLANE GEOMETRY FOR FIREFLY BOMBING

Using vector notation Equation (C-1) is rewritten as follows:

$$\overline{C}_P = \overline{S}_v \times \dot{\overline{R}}_p = \frac{R_p^{\,2} - R_R^{\,2}}{2\,V_a}\,\overline{\omega} \qquad \text{(C-2)}$$

Equation C-2 represents the vector solution to the correct release condition and the vectors on both sides of the equation must be equal in magnitude and direction. The approach used in the FIREFLY II mechanization is to treat the magnitude of the aircraft turn as an independent variable and find the bomb TOF (and the release point) which makes the magnitudes of the two vectors $\overline{C}_p$ and $\overline{\omega}$ equal. The direction of the two vectors $\overline{C}_p$ and $\overline{\omega}$ is then made equal by rotating the angular rate vector by controlling roll rate, which steers the aircraft toward the release point.

Ordinarily, the pilot controls the aircraft turning rate by moving the stick laterally until the desired bank angle (ϕ) or the desired yaw rate ($r_w = \frac{g}{V} \sin\phi$) is achieved, after which the stick is returned to the neutral position. Therefore, in a steady turn, the roll rate about the wind axis is zero, and hence in wind coordinates the vectors $\overline{S}_v$, $\overline{\omega}$ and $\overline{C}_p$ are defined by

$$\overline{S}_v = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \; ; \; \overline{\omega} = \begin{bmatrix} 0 \\ q_w \\ r_w \end{bmatrix} \; ; \; \overline{C}_p = \begin{bmatrix} C_{P1} \\ C_{P2} \\ C_{P3} \end{bmatrix} = \begin{bmatrix} 0 \\ -R_{P3} \\ R_{P2} \end{bmatrix} \qquad \text{(C-3)}$$

The pilot can also command a pitch rate by moving the stick longitudinally if he so desires to make a bombing approach on a nonhorizontal turning plane. The vector sum of pitch rate (q_w) and yaw rate (r_w) determines the magnitude of the turning rate ($\overline{\omega}$). The TOF is computed such that the magnitudes of the vectors in Equation (C-2) are made equal; and that is:

$$|C_p| = |\overline{S}_v \times \overline{R}_p| = \left(\frac{R_p^{\,2} - R_R^{\,2}}{2\,V_a}\right) |\overline{\omega}| \qquad \text{(C-4)}$$

The roll control law is obtained from the requirement that the directions of the vectors $\overline{C}_p$ and $\overline{\omega}$ be made equal. Since both vectors $\overline{C}_p$ and $\overline{\omega}$ are in the plane perpendicular to the wind axis, the angular error between those vectors is

$$\varepsilon = C_{P3} \cdot q_w - C_{P2} \cdot r_w \qquad \text{(C-5)}$$

The error ϵ vanishes when the vectors C_p and $\overline{\omega}$ are colinear. Therefore, the FIREFLY II control strategy is to feed the error ϵ into the roll axis control system in such a way as to null the error ϵ as shown in Figure C-2 below.

Because of the inherent integration between the commanded roll rate and the achieved bank angle, the error ϵ will be nulled and the direction of the vectors $\overline{C}_p$ and $\overline{\omega}$ will be made equal in the steady state, by controlling yaw rate (r_w) via aircraft body roll rate (p).

3. PROPOSED ROLL/PITCH CONTROL LAW MODIFICATIONS FOR THE A-10

There are two possible approaches for adapting the FIREFLY II bombing control laws to the A-10. The first approach retains the basic FIREFLY II control philosophy while using the pitch axis control system (instead of the roll-axis control system) to

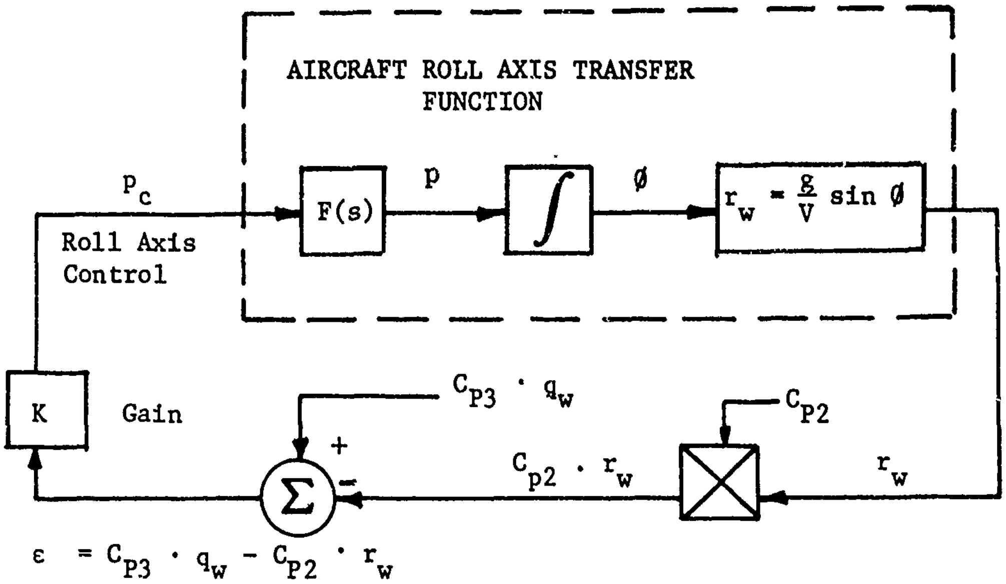


FIGURE C-2. FIREFLY II ROLL AXIS CONTROL SYSTEM

steer the aircraft. The second approach reverses the functions of steering control and TOF computation as described below.

<u>First Approach</u>

- The pilot sets the magnitude of the turn rate $|\overline{\omega}|$ by specifying a yaw rate.
- TOF is computed such that the magnitudes of the vectors $\overline{C}_p$ and $\overline{\omega}$ are made equal.
- The direction of $\overline{\omega}$ is adjusted automatically by controlling pitch.

The equations for computing the TOF unmodified. The aircraft control law, however, is modified as shown in Figure C-3.

Notice that a proportional plus integral controller is needed in the pitch control loop in order to achieve essentially zero error ϵ and ensure that the directions of the vectors $\overline{C}_p$ and $\overline{\omega}$ are the same in the steady state.

<u>Second Approach</u>

- In this approach the pilot still sets the approximate magnitude of $|\overline{\omega}|$ by adjusting yaw rate.

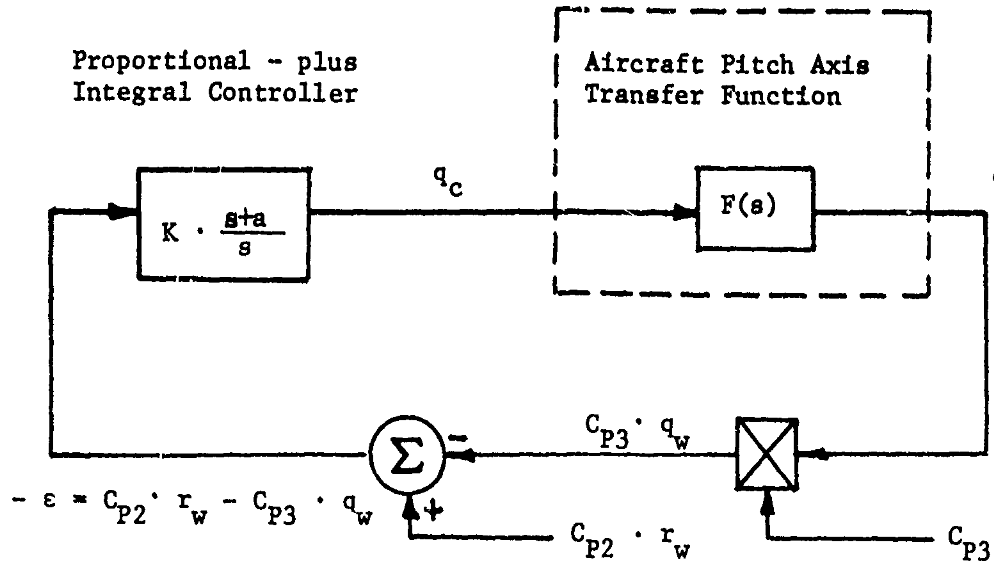


FIGURE C-3. PROPOSED PITCH AXIS CONTROL SYSTEM NO. 1 FOR THE A-10

- Pitch axis control system adjusts the magnitude of $\overline{\omega}$ until the magnitudes of the vectors in Equation (C-4) are made equal.
- TOF is then computed such that the direction of the two vectors $\overline{C}_p$ and $\overline{\omega}$ is made equal.

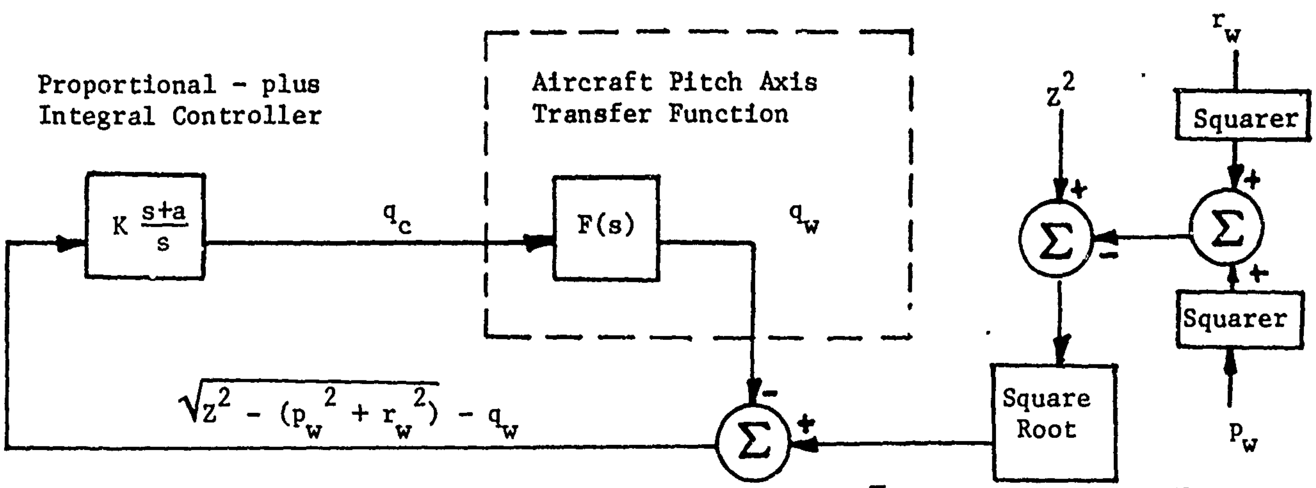
From Equation (C-4) one has:

$$|\overline{\omega}| = \sqrt{p_w^2 + q_w^2 + r_w^2} = \frac{|\overline{S}_V \times \overline{R}_P|}{R_P^2 - R_R^2} \cdot 2 V_a \qquad \text{(C-6)}$$

Since the right hand side is independent of the magnitude of $\overline{\omega}$, equality can be achieved by adjusting q_w. The pitch axis control system for the second approach takes the form of Figure C-4.

Because of the square root operation, the control system in Figure C-4 should not be engaged unless $Z^2 > p_w^2 + r_w^2$. This condition can be achieved by simply decreasing the turn rate magnitude.

The relationship for computing the TOF is then obtained by nulling the error ϵ in Equation (C-5). A Newton-Raphson algorithm similar to the one used in the



$$Z^2 = \left[\frac{|\bar{S}_v \times \bar{R}_p|}{R_p^{\,2} - R_R^{\,2}} \cdot 2\,V_a \right]^2$$

FIGURE C-4. PROPOSED PITCH AXIS CONTROL SYSTEM NO. 2 FOR THE A-10

FIREFLY II mechanization can be used for this purpose. The recursive equation for TOF is:

$$(t_f)_{n+1} = (t_f)_n - \frac{(\varepsilon)_n}{\left[\frac{\partial \varepsilon}{\partial t_f}\right]_n} \tag{C-7a}$$

$$\varepsilon = R_{P2} \cdot q_w + R_{P3} \cdot r_w \tag{C-7b}$$

$$\frac{\partial \varepsilon}{\partial t_f} = \frac{\partial R_{P2}}{\partial t_f} \cdot q_w + \frac{R_{P3}}{\partial t_f} \cdot r_w \tag{C-7c}$$

The partial derivatives $\partial R_{P2}/\partial t_f$, $\partial R_{P3}/\partial t_f$ must be evaluated in closed-form or numerically before a solution can be obtained for t_f. The convergence properties of this recursive equation must be verified through simulation.

4. FUTURE WORK

Other methods for adapting the FIREFLY II bombing algorithms to the A-10 should also be investigated, and the most promising approach should be selected on the basis of a simulation study. One method which appears feasible is to equate the components of vectors $\bar{C}_p$ and $\bar{\omega}$. $\left(\frac{R_P^{\,2} - R_R^{\,2}}{2\,Va}\right)$ along the v_w and w_w wind axes instead of the direction and magnitudes of the respective vectors.